APPLICATION OF PLASMA ARC

TO BEVEL CUTTING

MARAD PROJECT SP- 1-500

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FOREWORD

The purpose of this report is to present the results of one of the research and development programs which was initiated by the members of the Ship production Committee of The Society of Naval Architects and Marine Engineers and financed largzly by government funds through the cost sharing contract between the U. S. Maritime Administration and Bethlehem Steel Corporation. The effort of this project was directed to the development of improved methods and hardware applicable to shipyard welding in the U. S. shipyards.

MR W. C. Brayton, Bethlehem Steel Corporation, was the Program Manager. Mr. John A. Hogan and Mr. R. W. Couch of Hypertherm Inc. designed the equipment and directed the testing at the Sparrows Point Shipyard.

Special acknowledgement is made to the members of Welding Panel sP-7 of the SNAME Ship Production Committee who served as technical advisors in the preparation of inquiries and evaluation of sub-contract proposals.

SUMMARY

This report summarizes our assessment of plasma plate edge preparation. One, two and three torch bevel configurations were evaluated.

Special controls were developed which automatically ignite the trailing torches as they pass over the edge of the workpiece, and accurately maintain the torch-to-work distance of the torches during the cut.

One and two torch plate edge preparation appears to be practical for shipbuilding applications. Three torch beveling is not practical with the present technology; it is impossible to produce a condition which is dross-free. The joint configuration studied in the two torch case was the single bevel with a nose edge preparation. This geometry does have a process limitation: The bevel depth cannot exceed a value determined by the bevel angle and the nozzle size (kerf width) ; otherwise, dross will appear along the bottom edge of the nose. This does not appear to be a serious constraint on 3/4, 1, and 1 l/4-inch plate, but may pose a problem on 1 l/2-inch plate.

The best results for two and three torch plasma plate edge preparation are obtained by cutting the top bevel first, square cut second, and in the case of three torch beveling, the bottom bevel third. This is the reverse of the normal cut sequence employed for oxy-fuel multitorch beveling. Reversing the cut sequence pushes the dross down to the bottom edge rather than washing it over previously cut surfaces. In the case of two torch beveling, the conditions can be adjusted so that the plasma jet developed by the last torch provides sufficient momentum to prevent dross adherence. In the case of three torch beveling, dross formation along the edge of the bottom bevel cannot be avoided.

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1.0 INTRODUCTION

Plasma cutting has become widely accepted for certain shipbuilding applications. These applications are generally limited to shape cutting bulkheads, stiffeners, deckplates, etc. Until now, no attention had been given to the possibility of two and three torch plate edge preparation despite the advantages of higher cutting speeds and lack of distortion.

Plasma cutting is most advantageous in cutting relatively thin plate because the cutting speed is inversely proportional to plate thickness. The equation,

$$S=50/T$$

closely approximates the relationship between cutting speed, S in inches per minute and plate thickness, T in inches. However, in beveling applications the width of the cut face, not the plate thickness, determines cutting speed. For example, in order to bevel l/2-in. plate to 45 degrees, the cutting condition must be set for 3/4-in. plate to more closely correspond to the width of the cut face (.71 inches) . The follOwing equation approximates the cutting speed for single torch beveling:

$$S=50 \cos\beta/T$$

The term β is the bevel angle in degrees, measured with respect to the vertical. This equation also predicts the cutting speed for two and three torch beveling because both cases are limited by the slowest torch; i.e., the first bevel torch. Therefore, two and three torch beveling speeds could range from about 70 ipm for 5/8-in. plate to 30 ipm for 1 l/2-in. plate, assuming a 30 bevel angle. These speeds are two to five times faster than corresponding oxy-fuel beveling speeds.

This report summarizes the results of the MARAD sponsored program to investigate the feasibility of two and three torch plasma beveling. The following objectives were set forth in the original proposal.

(1) Develop the equipment necessary to study the feasibility of two and three torch plasma beveling.

(2) Develop operating conditions and document results.

(3) Determine process limitations in terms of maximum plate thickness, maximum bevel angle, etc.

(4) Develop general guidelines where plasma plate edge preparation should be applied. These guidelines are to be based on both economic and bevel quality guidelines.

2.0 EQUIPMENT

The Hypertherm PAC-500 Water-injection Plasma Cutting System was well suited for this program since it contained all the basic elements: Wide dross free cutting range, insulated torch front end, arc ignition reliability, and high cutting speeds. Several problems had to be overcome to make this system suitable for beveling. First, the front end profile of the torch had to be reduced to allow the torch to get close enough to the work for a quality cut. Second, the problem of igniting as many as three torches at different intervals had to be solved; otherwise, a waster plate would be necessary for each start up. Third, an accurate means of maintaining torch height had to be developed. Fourth, a mounting fixture which would allow various torch angles to be set had to be designed and built.

2.1 Plasma Cutting System

The three torch beveling system consists of a slightly modified Hypertherm three torch PAC-500 Water-injection Plasma Cutting System. This system is comprised of an operator's panel, three consoles and three torches with leads. The "operator's Panel" includes all the flow controls, mode select switches, etc., and is physically small, enough to be mounted near the operator. The console contains the solenoids, flow and pressure interlocks, and the high frequency arc ignition unit. One console is required per torch. The torches are water-injected type plasma torches. Water is injected radially into the arc in the form of a high velocity spray to constrict the arc into a finely focused heat source. A more complete description of this process is given in Appendix I. Torch lead length in this case is 30 feet.

All the major components of the plasma system - the operator's panel, console and torches are shown in Figure 1. The intercon-nection of each component is shown schematically in Figure 2.

The standard front end geometry of the Model 0 torch is flared as shown in Figure 3. A flared front end is normally used to improve the efficiency of the Water-Muffler. For beveling, however, the flared front end geometry restricts the ability to move the nozzle sufficiently close to the workpiece. A special tapered front end piece (nozzle retaining cap) was designed to allow the torch to operate at the desired torch-to-work distance for bevel angles up to 40 degrees (torch angle measured with respect to the vertical) .

2.2 Torch Height Control

An accurate means of controlling the torch-to-work distance is necessary if a consistent plate edge configuration is to be cut. For this investigation, the torch height control must hold ± .030 in. (.75 mm) for best results. Fortunately, one recent development - the THC-2 torch height control - made this requirement easy to satisfy.

The THC-2 adjusts the height of the torch to produce an arc voltage equal to a reference voltage. The reference voltage is set by means of a digital thumbwheel. If the torch is too high, the arc voltage will be greater than the reference voltage and the THC-2 will activate the torch suspension to move down. Conversely, if the arc voltage is lower than the reference voltage, the THC-2 will move the torch up. This technique is accurate to within + .030 inch. In addition, the THC-2 does not have the shortcomings of capacitive or fluidic height sensors. For example, the THC-2 will accurately maintain torch height while cutting near the edge of the plate, and it is totally unaffected by splash from the Water-Muffler.

The THC-2 Torch Height Control is shown in Figure 4. It governs the height of the lead torch only. The lagging torches are mechanically coupled to the lead torch by means of a torch mounting fixture (described in the next section) .

2.3 Torch Mounting Fixture

The torch mounting fixture consists of three adjustable mounting blocks . The complete torch mounting fixture is mounted to an MG Cutting Systems heavy-duty torch lifter as shown in Figure 5.

Since the design requirements were not fully defined for three torch beveling, it was decided to make the torch mounting fixture as simple as possible. Torch angle was changed by simply changing mounting blocks. The relative position of the leading and lagging torch could be changed in two ways: moving the torch up and down along the axis of the torch mounting block bore; and transversely moving the entire mounting block with respect to the middle torch (maximum transverse movement is 3-inches) . The middle torch mounting block was in most cases fixed square with respect to the workpiece; the primary degree of freedom was moving the torch up or down.

Torch cutting sequence is changed simply by reversing the direction of travel. For example, in Figure 5, the “top bevel first” cut is made by traversing right to left.

Two torch plate edge preparation is done by simply turning one of the torch stations off and making the square (middle) torch either leading or lagging.

2.4 Arc Ignition Sequencer

One problem that had to be solved was igniting all three (or two) torches in the proper sequence. This could, of course, be accomplished by using a “waster plate”, however, the waster plate approach is not a practical solution.

A control called the “Arc Ignition Sequencer” was developed to fire the trailing torch(s) as they pass over the edge of the workpiece. This is a relatively straightforward timing problem since both the torch separation distance and the cutting speed are known. The sequence of events are as follows:

1. The leading torch is positioned over the workpiece by the operator.

2. The operator inputs the cutting speed to the arc ignition sequencer by means of a digital thumbwheel.

3. The Start command is given providing gas, water, and open circuit power on all three (two) torches.

4. The first torch starts and torch motion begins after a one second pierce delay.

5. The first internal timer, T_1, is started. It holds firing of the second torch for a period dependent on both the cutting speed and the initial starting acceleration.

$$T_1 = S/V + A$$

Where:

T_1 = first time delay
S = torch separation (1.5 inches)
V = cutting speed. Variable from 5 to 95 inches per minute.
A = Acceleration constant (adjustable to suit characteristic of torch motion device).

6. The ignition of the second torch starts another timer, T_2, which is purely dependent on cutting speed. Acceleration is not a factor since the torch motion device will be up to speed after 1.5 inches of travel.

$$T_2 = S/V$$

The arc ignition sequencer control is shown to the left of the plasma control in Figure 1. Operationally, it is quite simple to use. All the operator has to set is the cutting speed.-

2.5 Power Supply

Each plasma torch requires one Model H-600 power supply. This is a continuously adjustable 120 KW power source rated at 600 amperes, 100% duty cycle. The H-600 power supply is ideal for triple torch beveling of mild steel because its capacity allows the use of the high current nozzles. These nozzles have a wider dross-free cutting range on mild steel and provide a 15% to 25% increase in cutting speed. The subject of dross-free cutting range is covered separately in Appendix II.

The H-600 power supplies used in this investigation are shown in Figure 6.

3.0 TEST RESULTS

3.1 Square Cuts

The first phase of the investigation was to determine the dross-free operating range for 9/16, 3/4, 1, 11/4, and 1l/2-in. plate. This information is important in deciding which nozzle sizes to select for beveling various plate thickness and surface conditions. For example, l/2-in. plate typically has a much wider dross-free operating range than l-in. plate; similarly, primed (zinc or iron oxide) plate has a wider dross-free operating range than an untreated mill scale surface.

The cases where the dross-free range is narrow or even non-existent can usually be alleviated by using the next largest nozzle size operating at a higher arc current and cutting speed. The subject of dross and its effect on operating conditions is covered separately in Appendix II.

Test cuts on 9/16 through 1l/2-in. plate were excellent in terms of cut quality. Cut angle was typically within 1° of square, although there was slight top edge rounding on plates 1 inch and under. Figure 7 shows a sample cut on 9/16 and 3/4–in. unprimed plate. Dross was not a problem as long as the operating conditions listed in Table I were used.

Cut angle is in part a function of torch-to-work distance. If the torch is too close to the workpiece, the cut angle will be negative or undercut (Figure 8) ; conversely, if the torch is too far above the workpiece, the cut angle will be positive. The THC-2 provided extremely accurate control of torch-to–work distance. This control literally makes it possible to produce at will +1°, +1/2°, 0°, -1/2°, -1° cut angles simply by changing the arc voltage setting.

3.2 Single Torch Beveling

Operating conditions for single torch beveling are necessary to develop because these conditions determine the cutting speeds required for two and three torch beveling. As noted earlier, the first torch making the bevel is the “slowest” torch so the settings for the other torch(s) must be adjusted accordingly. Therefore, the cutting conditions obtained for single torch beveling also apply, to a large extent, to two and three torch beveling.

The maximum bevel angle investigated was 30°since most joint geometries employ an included angle less than 60°. In fact, the most recent one side subarc welding conditions specify a joint configuration with an included angle closer to 40°.

Excellent single torch bevel quality was obtained over the entire thickness range investigated. Single bevel cuts on plate up to 1l/4-in. were always dross-free; however, 1 l/2-in. plate was more difficult. It was generally necessary to bevel cut the 1 l/2-in. plate in the primed rather than the mill scale condition, and use the .220 nozzle (largest nozzle size) at 700 amperes; otherwise, dross was a problem. The .187 nozzle performed well on

1-in. and 1 l/4-in. plate while the .166 nozzle appeared best suited for 3/4-in. plate. Operating conditions are summarized *in* Table 11 for bevel angles of 20°and 30°.

Examples of single torch bevels are shown in Figure 9. In this case, the torch angle is set at 20° with respect to the vertical. Resulting cut angle is slightly greater than the torch angle; however, the difference seldom exceeds 2 degrees.

As explained in Appendix I, the Model 500 torch generally swirls the cutting gas in the clockwise direction. (Viewed looking down on the torch). The component that creates the gas swirl is called the “swirl ring” and is shown in Figure 3. Both clockwise and counterclockwise swirl rings are available.

The swirling action of the cutting gas forces the arc attachment points that form along the leading edge of the cut over to the right side of the kerf. The net effect of clock-wise swirl is that the right side of the cut with respect to the direction of travel is square, while the left side is beveled. Therefore, in shape cutting applications it is necessary to make outside cuts in a general clockwise direction and inside cuts in a general counterclockwise direction.

The impact of gas swirl on single torch beveling is twofold: (1) Clockwise swirl ring should be used whenever the beveling is performed on the right side with respect to-the direction of travel. (2) Applications which require beveling on the left side of the workpiece should use a counterclockwise swirl ring. The direction of gas swirl is not a very critical parameter. If the wrong gas swirl ring is used, the resulting bevel cut will be 4 to 6 degrees greater than the torch angle instead of 2 degrees. In addition, if the cutting condition is borderline, light dross may form along the bottom edge.

3.3 *Two* torch Beveling

The most common two torch plate edge geometry is the single bevel with *a* nose configuration shown in Figure 10A. In fact, with the recent advances in one side subarc welding, this joint geometry is becoming increasingly popular: the trend is toward a heavier nose section and a smaller bevel angle.

The other possible two torch joint configuration is the double bevel without a nose. This geometry is shown in Figure 10B. For reasons which will be explained later, this edge geometry did not turn out well. Most of the effort, therefore, was concentrated on the single bevel with a nose plate edge preparation.

3.3.1 Effect of Cut Sequence

Cutting sequence is of major importance in producing an optimun cut. Plasma cutting, unlike oxy-fuel cutting, is capable of jumping the kerf made by the preceding torch. As a result, two plasma torches can cut either “bevel torch first” or “square torch first” as shown in Figure 11. However, the cut edge generated by each cut sequence is remarkably different. The “bevel torch first” sequence produces by far the best results. In the case of the “square torch first” sequence, the metal expelled by the bevel torch washes over the nose cut by the lead torch and forms a tenacious, well fused layer of dross. The “bevel torch first” sequence, by contrast, works in reverse: The last (square) torch literally cuts off any dross created by the lead (bevel) torch. Both cut sequences are compared in Figure 12 for 3/4-in. plate. Identical results are obtained on the other plate thickness investigated.

3.3.2 Maximum Bevel Depth

The “bevel torch first” sequence does not always produce a dross-free cut. Under certain conditions dross will form along the bottom edge of the nose. Usually, this dross adheres in a thin line and requires grinding or chipping to remove. It was discovered that dross occurs whenever a scrap triangle is formed between the two cuts as shown in Figure 13. The scrap triangle disrupts the flow of molten metal off the leading edge of the kerf formed by the “square” torch. Instead of forming a high velocity spray of small droplets, the metal runs off the scrap triangle in large droplets. Another factor, is that the scrap triangle also causes the plasma effluent to expand on one side as it exits from the shallow kerf formed between the scrap triangle and the opposite kerf wall. The net effect is a rela-’ tively low velocity plasma jet in the lower regions of the.kerf. This condition produces dross because the molten metal is not accelerated to a sufficient velocity to overcome the surface tension forces acting to make the molten flow solidify along the bottom edge of the nose; consequently, a line of dross is formed.

This limitation could not be solved by varying process parameters. Different nozzle sizes, gas flows, gas swirl directions, and arc current settings were investigated. The only successful approach was to modify the joint geometry so that the scrap triangle would not appear; and secondly, select a nozzle as large as possible so that the wider kerf would tend to eliminate the scrap triangle.

Each nozzle size and bevel angle has a corresponding maximum bevel depth[1] that cannot be exceeded; otherwise, the scrap triangle which leads to dross will form. Since this limitation is not a function of plate thickness, the major implication is that the heavier the plate the wider the nose. For example, as shown in Table III, 3/4-in. plate has a minimum nose width of .31-inches; 1l/2-in. plate has a minimum nose width of .81-inches.

The data was determined empirically by increasing the bevel depth in the various plate thickness using a bevel angle of 27°. Figure 14 illustrates the dross cross-over point for 3/4-in. plate. This dross cross-over point is also shown in Figures 15, 16, and 17 for 1, 11/4, and 1l/2-in. plate respectively. The nozzle size used on plate above l-inch is the .220 nozzle.

1 Bevel depth is the vertical distance from the top of the workpiece to the line formed by intersection of the nose and bevel cut surfaces. Refer to Appendix III.

It is interesting to note that although the lead and lag torch anqles were fixed at 20° and O° respectively, the corresponding cut angles were 27° and 5° respectively. This result is somewhat surprising because in single torch beveling the torch angle almost exactly equals the resulting bevel angle. Apparently, there is sufficient magnetic interaction to deflect the plasma jet cutting the bevel. However, magnetic interaction could be secondary to other factors such as the “effective arc length” (measured from the torch to the beginning of the nose).

Bevel angle, as noted earlier, has a major effect on the formation of the scrap triangle. The derivation in Appendix III shows that the maximum bevel depth, D_β, is related to the bevel angle, β, and kerf width, W, by the following equation:

$$D_\beta = W/\sin\beta$$

In the case of the .220 nozzle, the kerf width is around .30-inches. Assuming a bevel angle of 27°, the predicted maximum bevel depth is .66 inches which agrees closely with the results summarized in Table III. Predicted maximum bevel depth is plotted against bevel angle for the .166 nozzle, .187 nozzle and .220 nozzle in Figure 18.

3.3.3 Effect of Primer

Whether or not the plate is primed does make a difference on 1 1/4 and 1 l/2-in. plate. As in the case of single torch cutting, primer made it easier to get a dross-free cut. This point, however, is probably academic since the most applicable results are obtained on 374 and l-in. plate where dross adherence was not noticeably dependent on plate surface condition.

3.4 Three Torch Beveling

The edge preparation attempted in this phase of the program was the double bevel with a nose edge geometry shown in Figure 19. Based on the problems encountered with the single bevel with a nose edge preparation, it is obvious that the degree of difficulty for this case will be much greater.

3.4.1 Cutting Sequence

In oxy-fuel cutting, the cut sequence is arranged so that the cutting stream does not cross a kerf. The only cut sequence that satisfies this condition is the following: Bottom bevel torch first, square torch second, top bevel torch last (see Figure 20) . As noted earlier, plasma cutting does not have this constraint so it is possible to cut in any sequence; the only iimitation of course, is the resulting cut quality.

The conventional oxy-fuel cut sequence was the first investigated. The resulting cuts were extremely inconsistent. In one instance, the effluent from the square and top bevel torches would roll over the bottom bevel and form a “dross casting” which could be easily removed in one piece with a chipping hammer; in another instance, the effluent would fuse to the bottom bevel and could not be removed. Both cases are shown in Figure 21. Unfortunately, the liklihood of the dross tenaciously fusing to the bottom edge is about four times greater than forming the easy to remove “dross casting”.

The direction of gas swirl was reversed in the last two torches in an attempt to bias the molten effluent to flow toward the scrap side of the kerf. Gas swirl had no measurable effect. Larger and smaller nozzles combinations were also tried with only limited success. The workpiece was even submerged in water in an attempt to force the dross to solidify before fusing to the cut edge. This also had no measurable effect. The results shown in Figure 21 are among the best three torch bevel samples that were produced during the study.

The cut sequence was reversed to the top bevel first, square torch second, and the bottom bevel last (see Figure 20). This scheme performed better in terms of dross, but worse in terms of cut edge geometry. Dross would be consistently pushed down to the bottom edge of the bevel as shown in Figure 22. Unfortunately, this dross is very tenacious. As can be seen in cross sectional view in Figure 22, the resulting edge geometry is nonuniform. This nonuniformity can be corrected by trial-and-error adjustment . of torch angle.

A variety of nozzle combinations, gas swirl ring designs, etc. were tested with no substantial improvement. It was concluded, therefore, that triple torch plasma beveling is not a practical tool - at least with the present state-of-the art.

One final attempt was made to produce the double bevel with a nose edge geometry in two separate passes. The first pass was made with two torches to produce a top bevel with a nose. As shown earlier, this can be done dross-free. The scrap side was removed and a second pass was then made to cut the bottom bevel. This procedure allows the second torch to operate unhindered by previously cut kerfs. Also, the second pass torch can be positioned closer to the top of the bottom bevel (closer torch-to-work distance). As shown in Figure 23, this approach did produce a more uniform edge geometry. However, a heavy line of tenacious dross consistently formed on the bottom edge.

3.4.2 Effect of Primer

Zinc primer had no measurable effect on the results of the three torch bevel tests. The propensity to produce dross on the bottom edge far exceeded the slight benefits gained by the primer.

4.0 ENVIRONMENTAL CONSIDERATIONS

4.1 Fumes

A single plasma torch cutting mild steel produces 4 to 6 pounds of fumes and particulates per hour. TWO or three plasma torches operating simultaneously would produce intolerable fume levels in a matter of minutes without proper fume control.

Most of the tests were conducted on a Water-Table cutting bed with the water just touching the bottom surface of the work-piece. This approach efficiently controlled the fumes and Pro- duced no deleterious effects on cut quality. Fume control efficiency appeared to be at least 95

4.2 Noise

Acoustical noise is a more difficult form of pollution to control. Normally, a plasma torch is operated vertical to the workpiece. In this case a Water-Muffler can be used to reduce the noise. The Water-Muffler is simply an annular collar that fits around the body of the torch and produces a heavy curtain of water around the arc. A Water-Muffler is shown in Figure 24.

Unfortunately, when the torch is tilted, this disrupts the flow of water around the torch. In addition, the wide kerfs produced by the lead torch(s) allows noise to escape. The amount of noise produced with and without a Water-Muffler is shown graphically in Figure **25** as function of bevel angle and arc current. Note that these results are for one torch. A two torch system would produce an additional 3 dBA, whereas a three torch system would produce an additional 5 dBA. These decibel increases are approximate since they do not take into considera- tion the fact that the torches are fixed at different angles and, therefore, the noise levels generated would be slightly different. This approximation, however, is sufficient for purposes of this discussion.

For example, consider a two torch beveling application with one torch inclined 20 degrees and the other torch square. If both torches are operated at 700 amperes, the total noise is approximately 104 dBA (101 + 3 dBA) with the Water-Muffler and 115 dBA (112 + 3 dBA) without the Water-Muffler. In either case, this noise level is quite high.

Several plasma users in Europe have found that accoustical noise can be greatly attenuated by submerging the front end of the torch in about 3-inches of water. This technique was reported to be even more effective than the Water-Muffler. We tested this concept for multiple torch beveling. It was found that the noise level drops to **82** dBA when the torch is vertical to the workpiece and **95** dBA when the torch is inclined **30** degrees.

Cutting with the plasma torches partially submerged under water has certain drawbacks. These are: (1) Initial (arc off) setting of the torch height is difficult to automate. (2) The workpiece is obscured by the water. (3) The water must be lowered to load and unload the workpiece.

Fortunately, in plate edge preparation applications only one or two long cuts are made per plate so it is practical for the operator to position the torch at the start of each cut. The fact that the workpiece is obscured by the water is not a serious problem since there is no real chance of a torch snagging on a previous cut piece. Lastly, raising and lowering can be done quickly with the Water-Table designs currently available. These Water-Tables employ air-over-water holding tanks to rapidly displace the water (raise) and to store the water (lower).

Submerging the torches will not affect torch height control since the height is maintained by sensing arc voltage. Arc voltage is completely unaffected by presence of water. The THC-2 torch height control scheme described earlier performs well in the water environment.

5.0 APPLICATIONS

The only joint configurations that appears.to be practical are one and two torch plate edge preparations. Three torch plate edge preparation does not appear feasible at this time.

The ultimate objective is to marry the capabilities of high speed plasma plate edge preparation with one of the high deposition welding processes. The most recent trend is away from triple torch plate edge preparations since welding is required on both sides. The results obtained in this program with two torch plate edge preparation appear to be compatible with most of the one side welding processes: Relatively shallow bevel angle (20°to 30°) and a relatively heavy nose section. However, there is a constraint on the maximum depth of bevel which, in turn, affects the nose dimension for a given plate thickness. This would have a bearing on which welding process to select. The practical operating range is defined in Figure 18 and Table III.

5.1 Economics

Plasma one and two torch plate edge preparation offers a tremendous speed advantage over the oxy-fuel process. For example, if the edge preparation is a 20°bevel with a nose, a two torch plasma beveling system would be roughly 3 1/2 times faster than its oxy-fuel counterpart. This speed difference is shown in Figure 26 for 3/4, 1, 1 1/4, and 1 l/2-in. plate.

Process economics are a function of cutting speed, duty cycle, labor rate and consumable costs. Since each shipyard will vary in all factors but cutting speed, it is not possible to develop a meaningful economic analysis. It generally is true, however, that the labor content accounts for 70% to 80% of the total cutting cost. Consequently, increasing the cutting speeds by a factor of 3.5 will reduce the cutting costs by almost the same factor.

A more exacting estimate of cutting cost can be obtained by applying the following equation.

$$W = \frac{20}{S}\left(100\,\frac{L}{ND} + G + H + J + K\right),$$

where:

W = Cutting Cost (¢/ft.)
N = Number of Torches
S = Cutting Speed (in./min.)
L = Labor and Overhead ($/hr.)
D = Duty Cycle (%)
G = Gas cost per Torch ($/arc hr.)
H = Nozzle Cost per Torch ($/arc hr.)
J = Electrode Cost per Torch ($/arc hr.)
K = power Cost per Torch ($/arc hr.)

TABLES

and

FIGURES

CUTTING CONDITIONS - SQUARE CUTS

Plate Thickness (inches)	Nozzle Size	Gas Flow (cfh)	Injection Water Flow (gpm)	Torch-to-Work Distance (inches)	Arc Voltage	Arc Current (amps)	Cutting Speed (ipm)
9/16	.166	165	.38	1/4	160	400	90
3/4	.166	165	.38	1/4	160	400	60
3/4	.187	165	.38	5/16	170	550	75
1	.187	165	.38	3/8	175	550	55
1¼	.187	165	.38	3/8	175	600	45
1½	.220	260	.48	3/8	180	700	35

Table I

CUTTING CONDITIONS - SINGLE TORCH BEVEL

Plate Thickness (inches)	Nozzle Size	Gas Flow (cfh)	Injection Water Flow (gpm)	Arc Voltage	Arc Current (amps)	Cutting Speed (ipm)
20° Bevel						
¾	.166	165	.38	165	400	58
1	.187	165	.38	175	550	48
1¼	.187	165	.38	180	600	44
1½	.220	260	.48	190	700	33
30° Bevel						
¾	.166	165	.38	165	400	53
1	.187	165	.38	175	550	44
1¼	.187	165	.38	180	600	41
1½	.220	260	.48	190	700	30

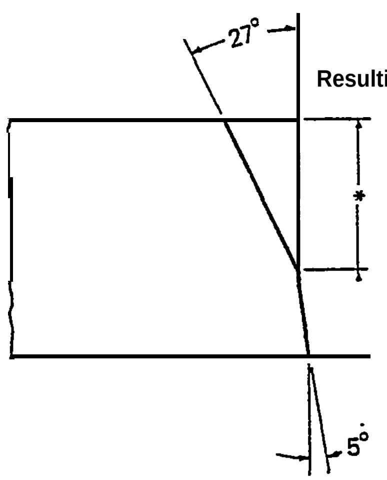
Table II

CUTTING CONDITIONS - TWO TORCH BEVEL

Plate Thickness (inches)	Nozzle Size	Gas Flow (cfh)	Injection Water Flow (gpm)	Arc Voltage	Arc Current (amps)	Cutting Speed (ipm)	Maximum * Bevel Depth (inches)	Minimum Nose Width (inches)
¾	.166	165	.38	165	400	58	.38	.37
¾	.187	165	.38	175	575	68	.44	.31
1	.220	260	.48	185	700	53	.69	.31
1¼	.220	260	.48	185	700	40	.69	.56
1½	.220	260	.48	190	700	40	.69	.81

Table III

Resulting Edge Geometry



Notes:

1. Both torches are operated at the above settings.
2. No. 1 Torch is inclined 20° from the vertical.
3. No. 2 Torch is square.
4. Positive nose angle can be eliminated by utilizing an inclination of −5° on Torch No.2.

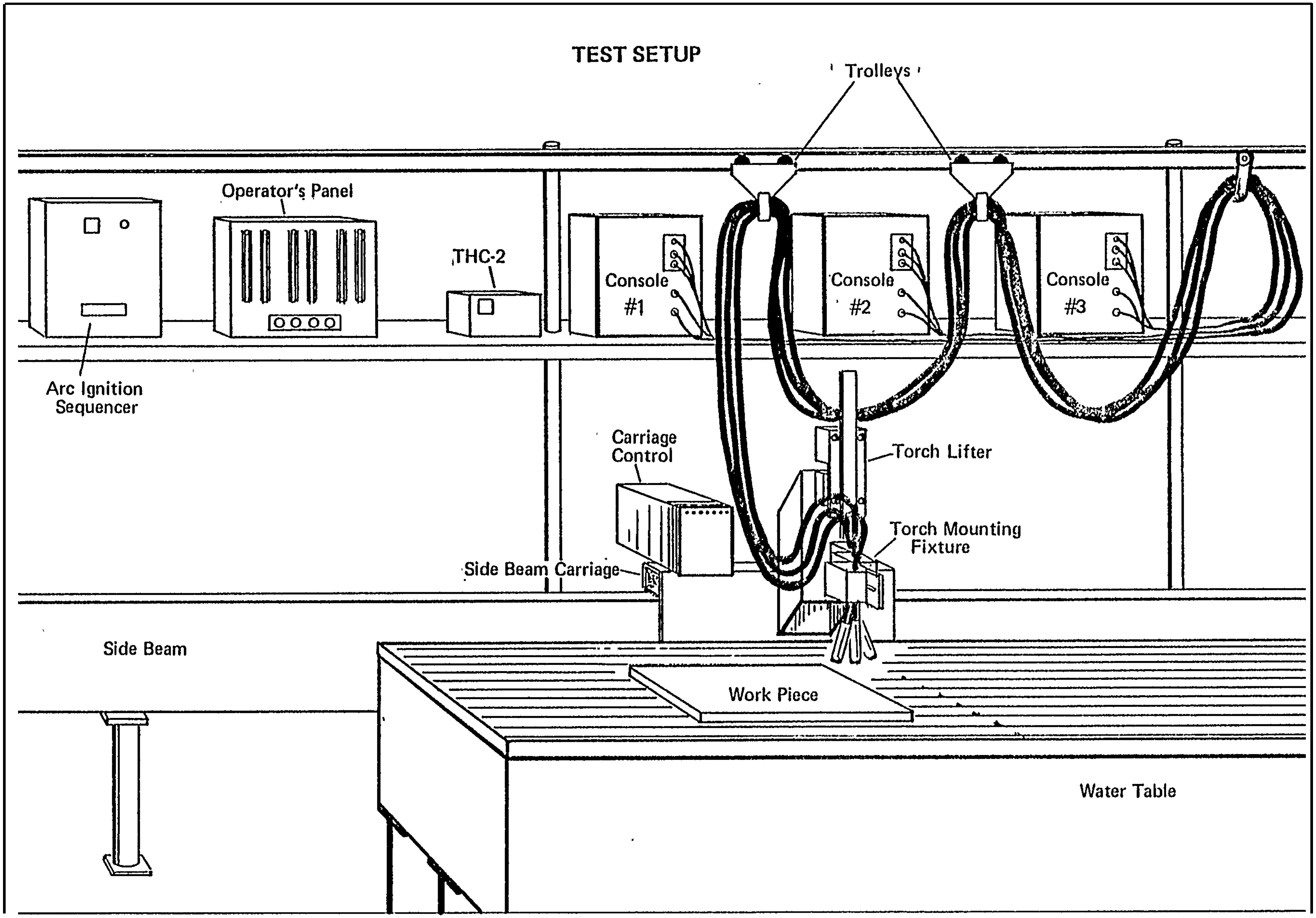
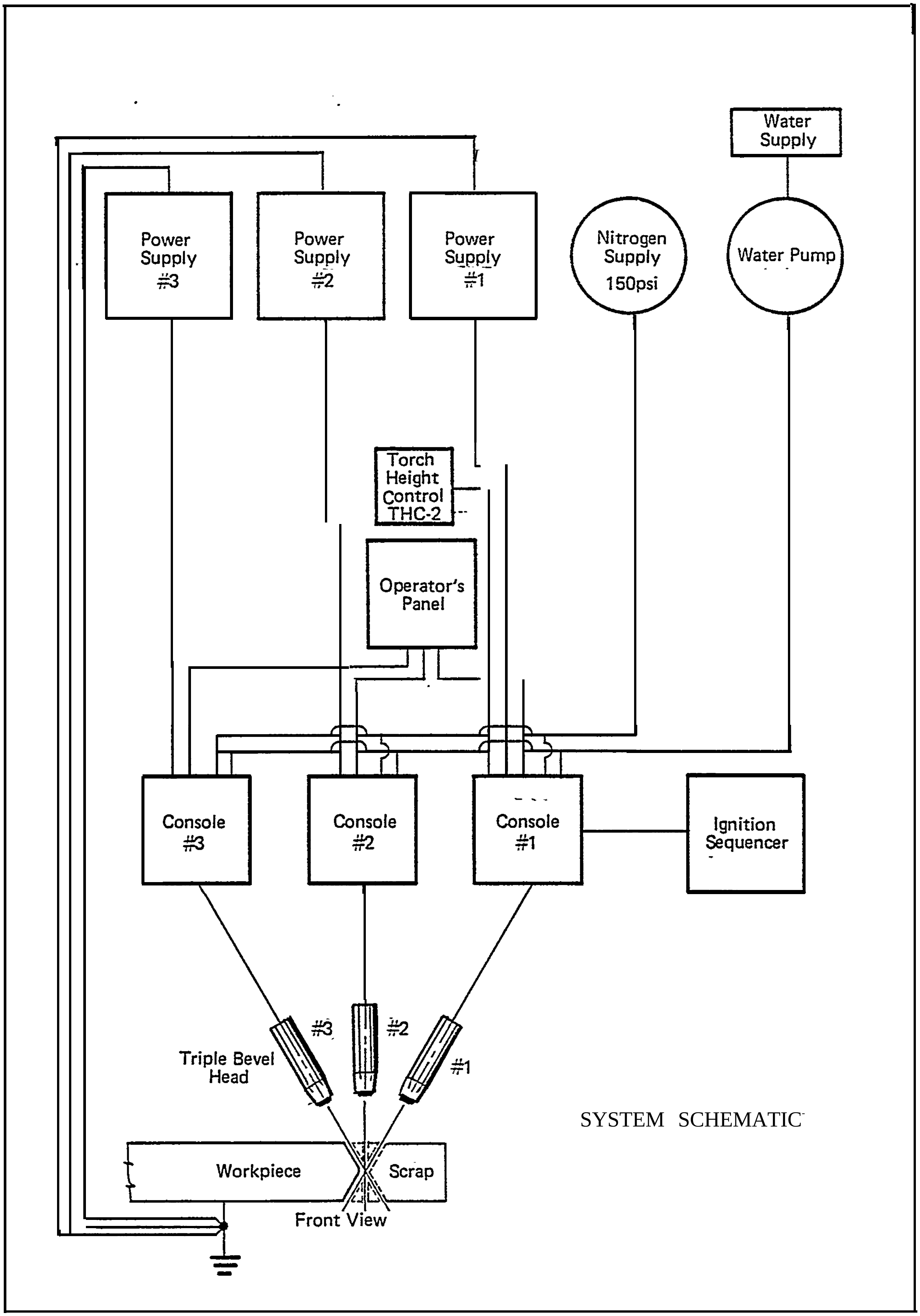

TEST SETUP
Trolleys
Operator's Panel
THC-2
Console
#1
Console
#2
Console
#3
Arc Ignition
Sequencer
Carriage
Control
Torch Lifter
Torch Mounting
Fixture
Side Beam Carriage
Side Beam
Work Piece
Water Table

Figure 1



Water Supply
Power Supply #3
Power Supply #2
Power Supply #1
Nitrogen Supply 150psi
Water Pump
Torch Height Control THC-2
Operator's Panel
Console #3
Console #2
Console #1
Ignition Sequencer
#3
#2
#1
Triple Bevel Head
SYSTEM SCHEMATIC
Workpiece
Scrap
Front View

Figure 2

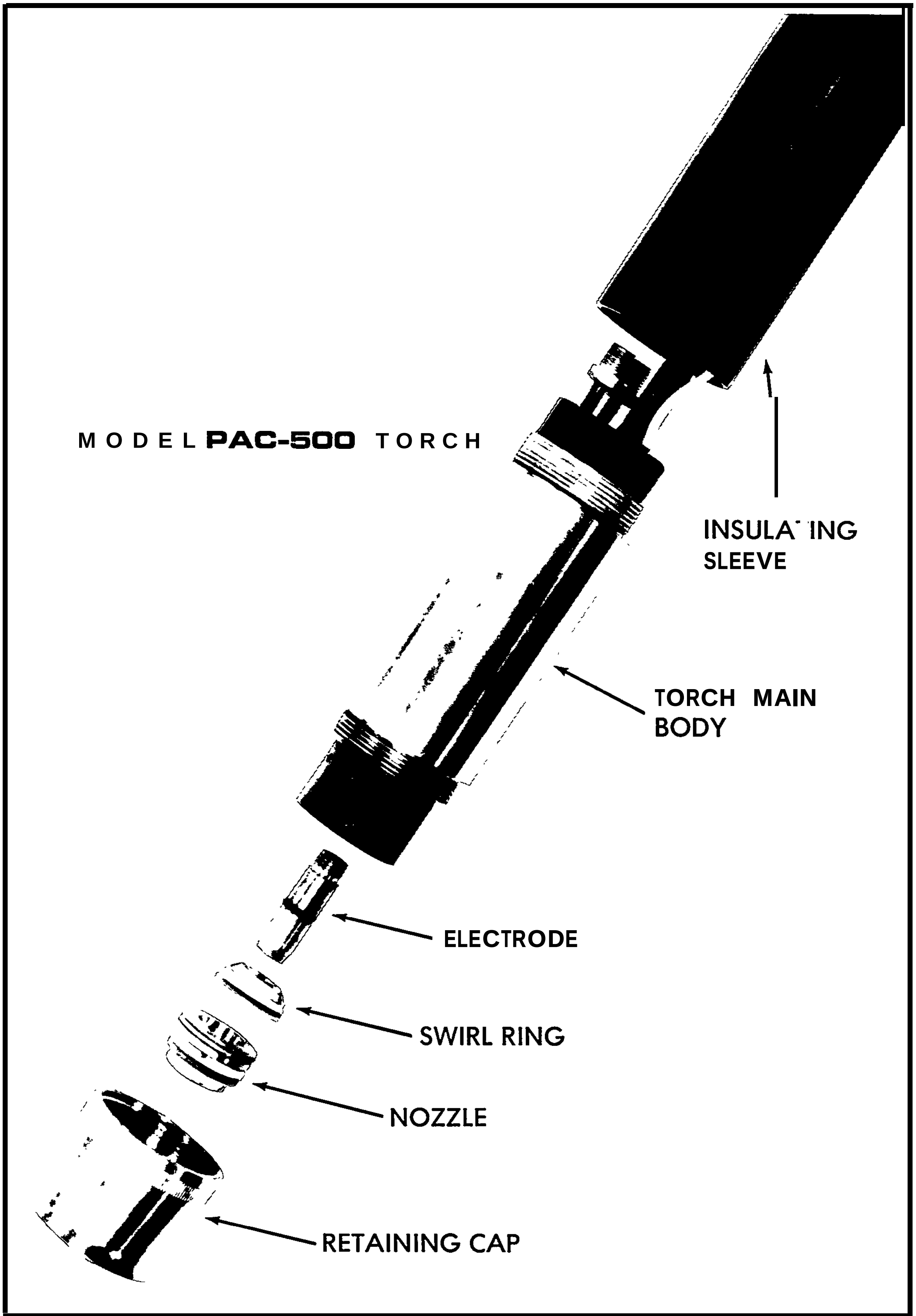
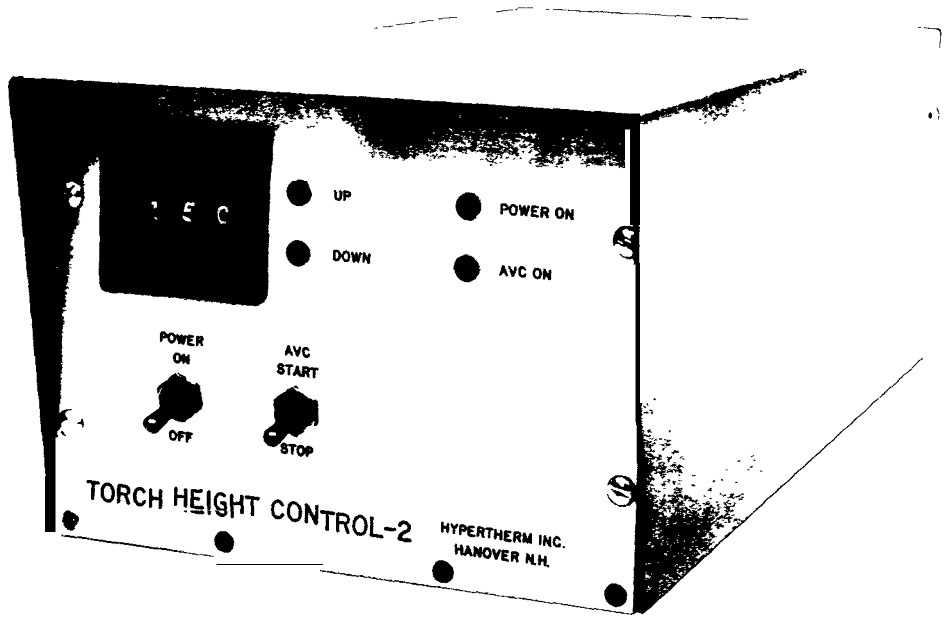

MODEL PAC-500 TORCH
INSULA' ING SLEEVE
TORCH MAIN BODY
ELECTRODE
SWIRL RING
NOZZLE
RETAINING CAP

Figure 3



TORCH HEIGHT CONTROL

Figure 4

TORCH MOUNTING FIXTURE

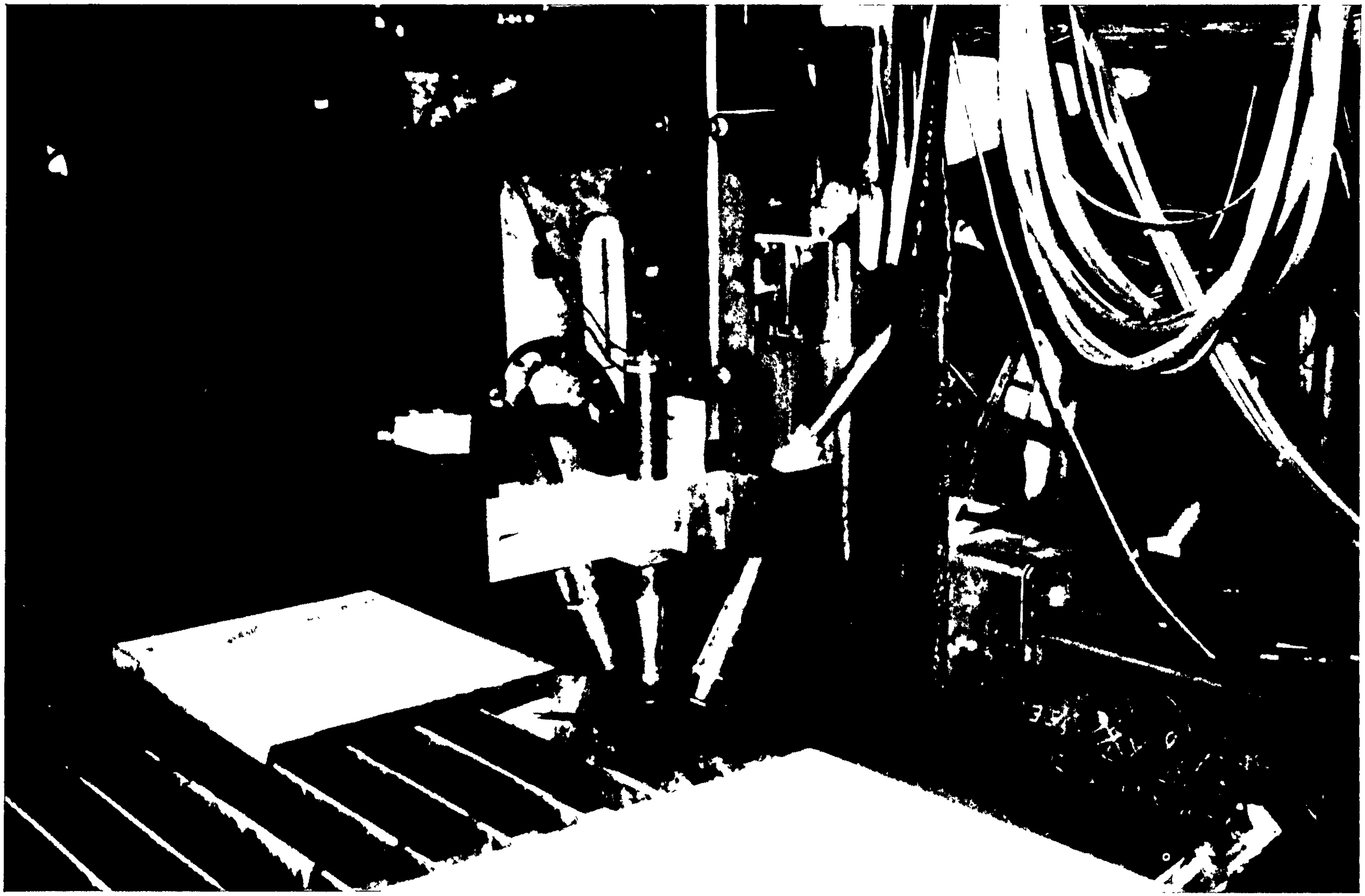


Figure 5

H-600 POWER SUPPLY

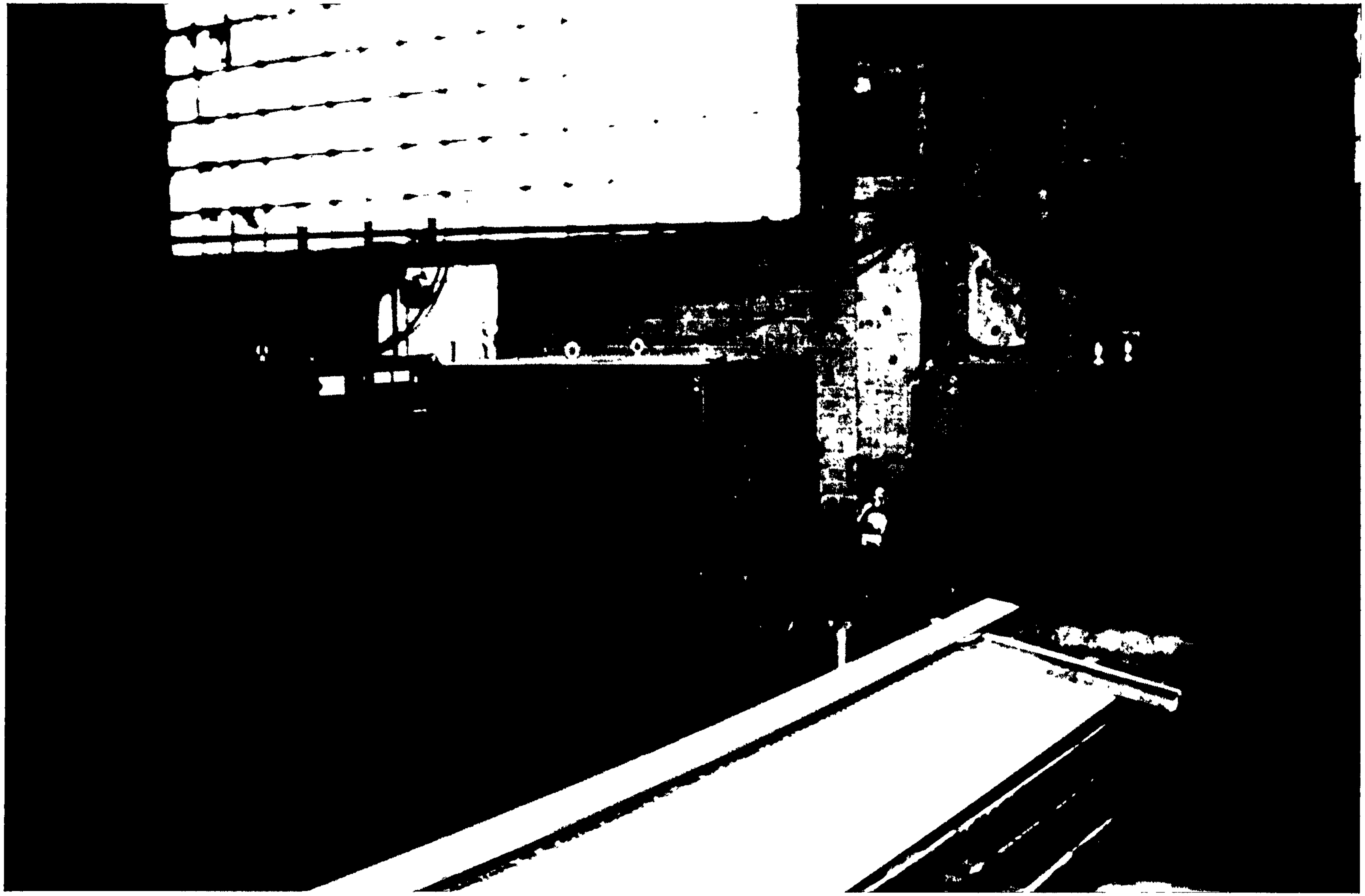
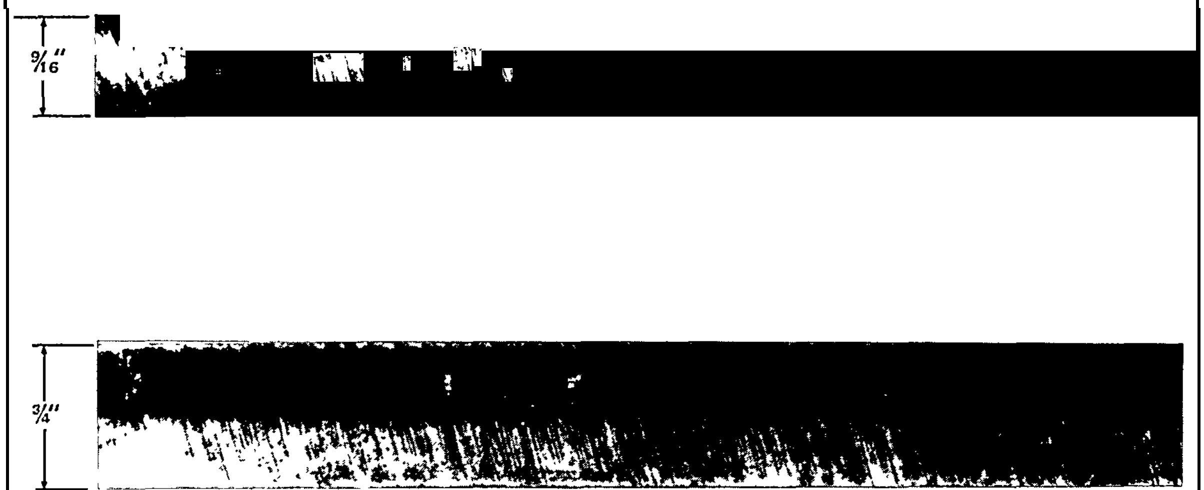


Figure 6

SQUARE CUTS



Note: Refer to Table I for cutting Conditions

Figure 7

DEFINITION OF POSITIVE AND
NEGATIVE CUT ANGLE

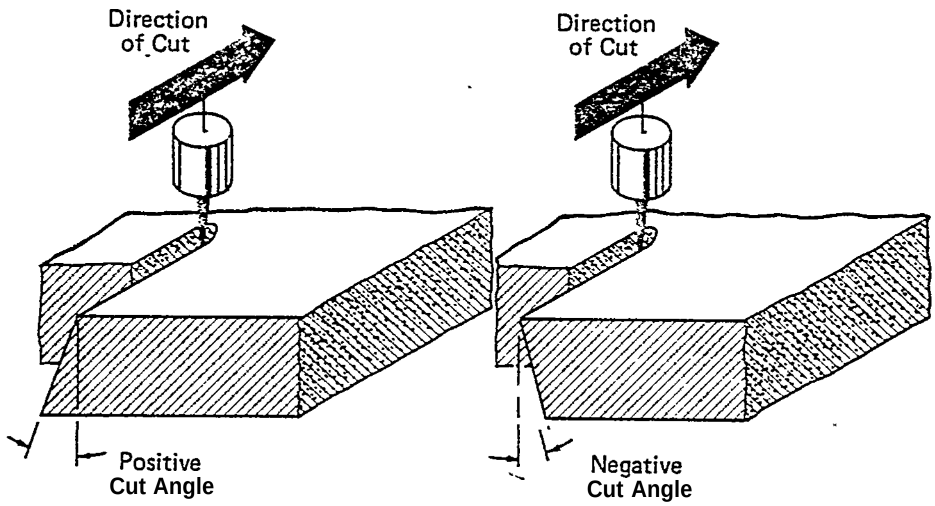


Figure 8.

SINGLE TORCH BEVELS

Notes: Bevel Angle=22°.
Refer to Table II
for cutting conditions.

Figure 9

SINGLE BEVEL WITH NOSE EDGE PREPARATION

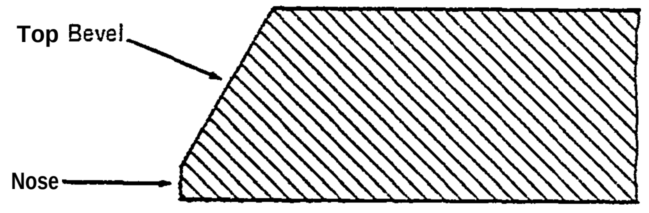


Figure 10A

DOUBLE BEVEL WITHOUT NOSE EDGE PREPARATION

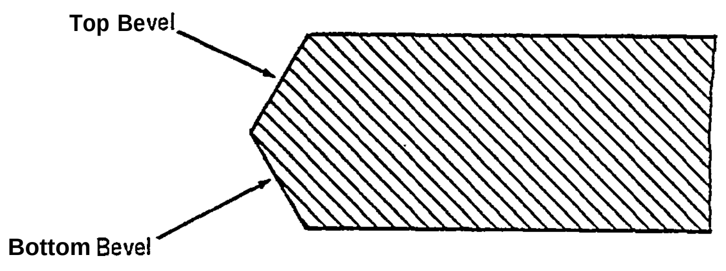


Figure 10B

TWO TORCH BEVELING

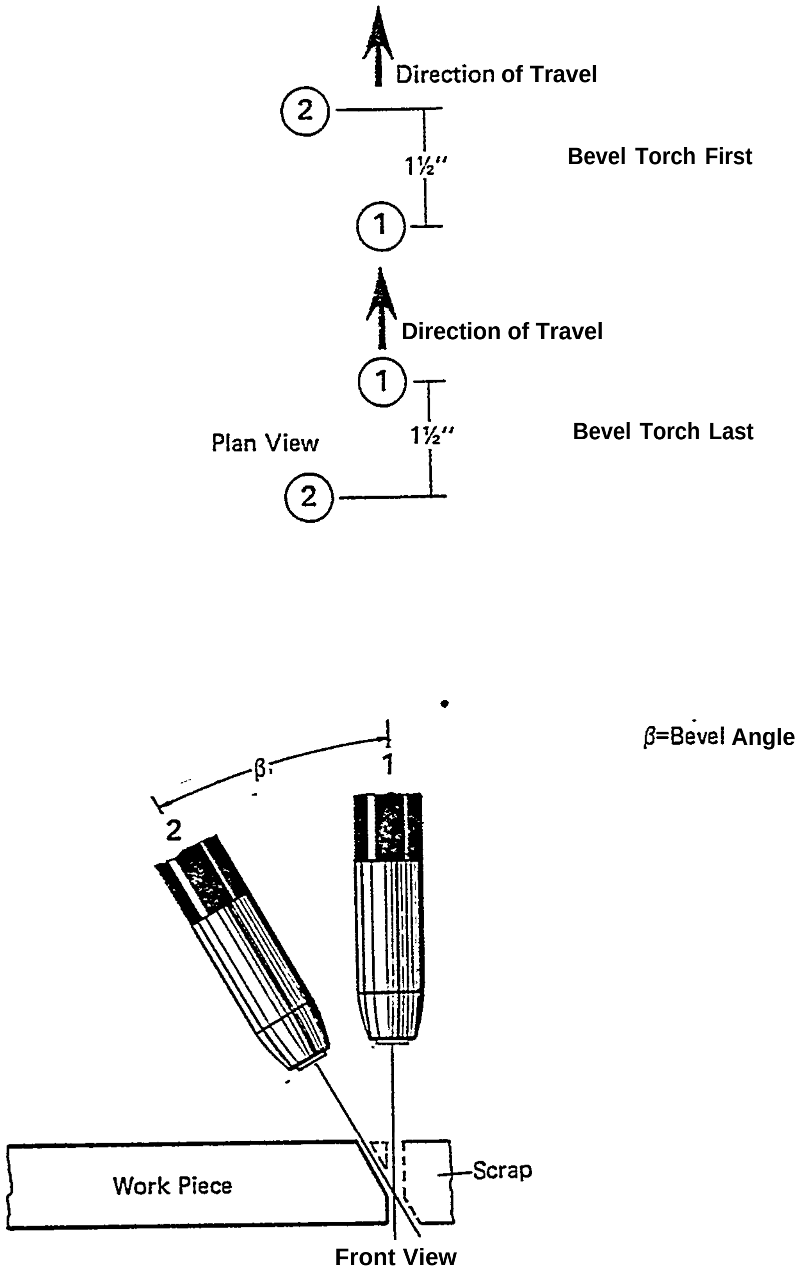


Figure 11

EFFECT OF CUT SEQUENCE - TWO TORCH BEVELING

Square Torch First.

Bevel Torch First.

Figure 12

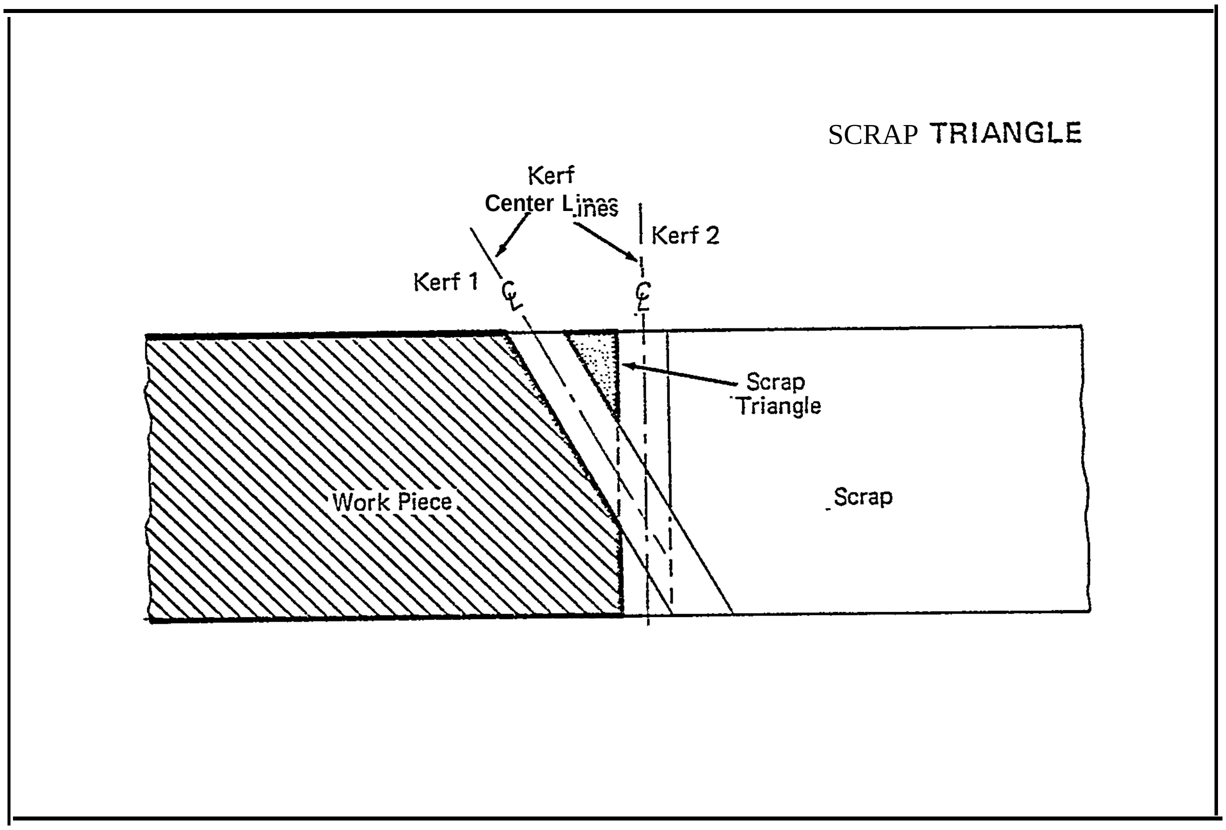
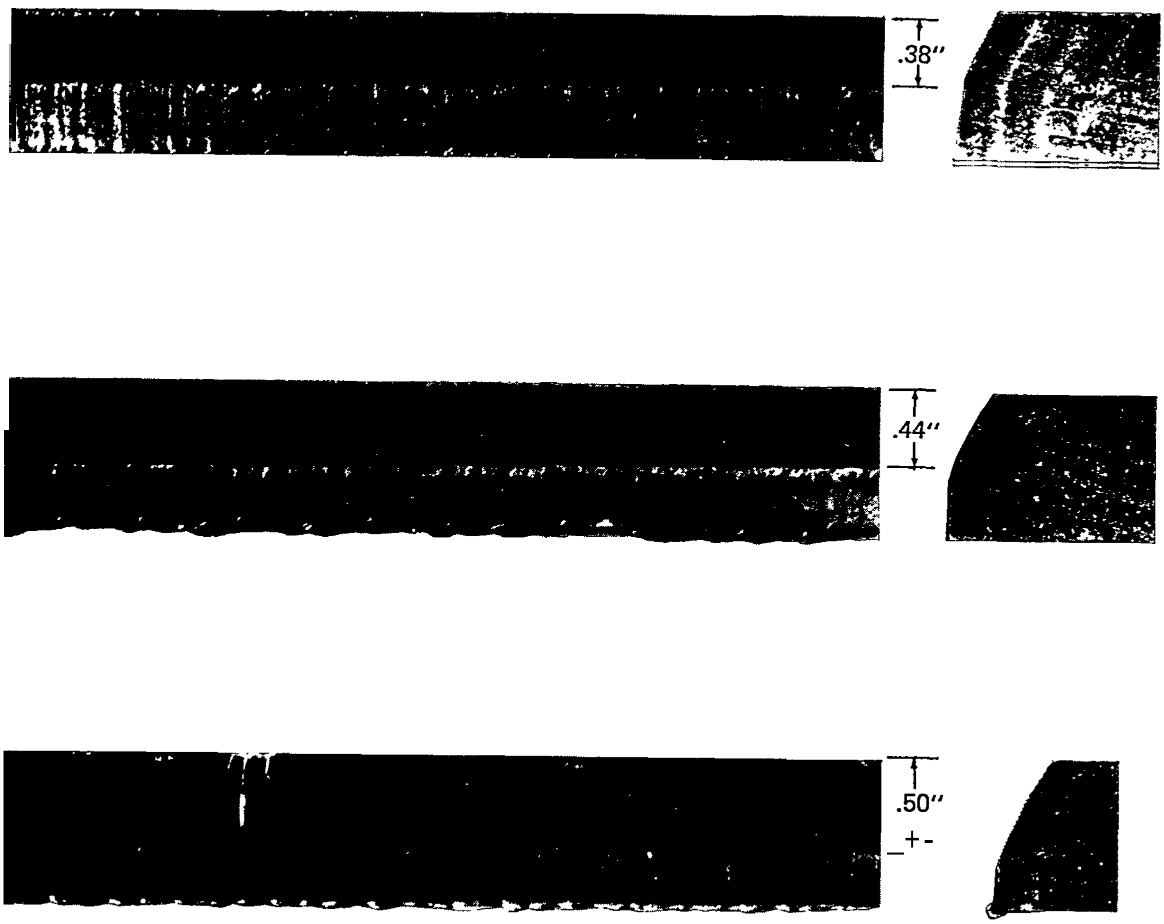

SCRAP TRIANGLE
Kerf
Center Lines
Kerf 2
Kerf 1
Scrap
Triangle
Work Piece
Scrap

Figure 13

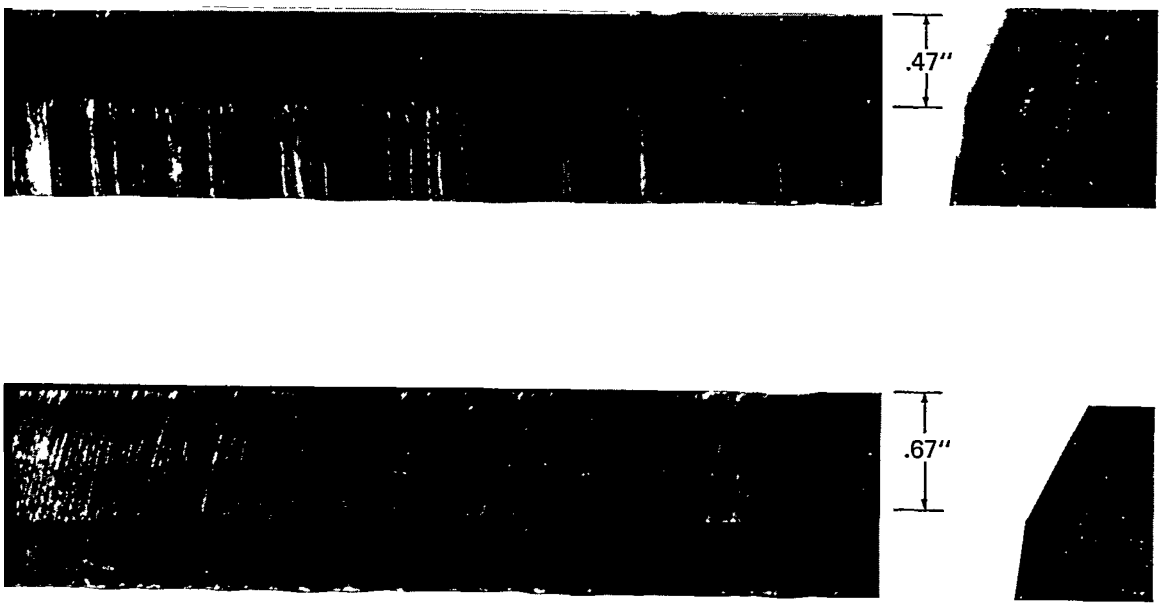
EFFECT OF BEVEL DEPTH ON DROSS FORMATION - ¾" PLATE



Notes: Bevel Angle=27°.
Nose Angle=5°
Refer to Table III
for cutting conditions.

Figure 14

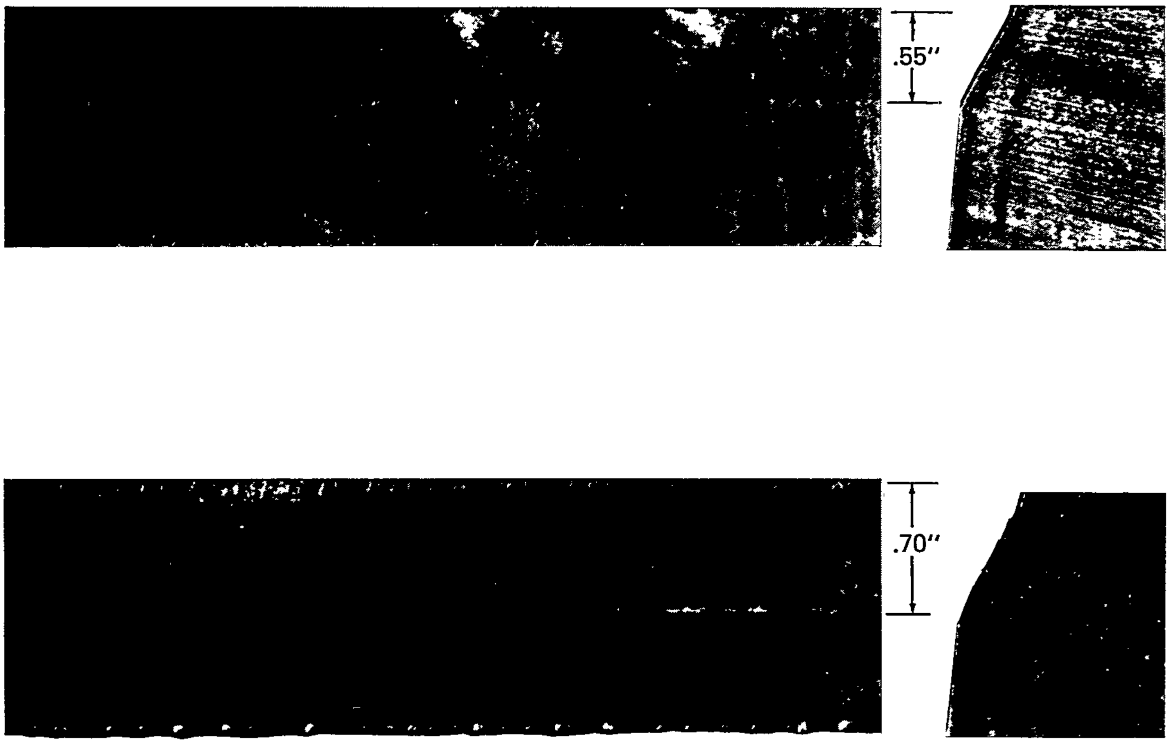
EFFECT OF BEVEL DEPTH ON DROSS FORMATION - 1" PLATE



Notes: Bevel Angle=27°.
Nose Angle=6°.
Refer to Table III
for cutting Conditions.

Figure 15

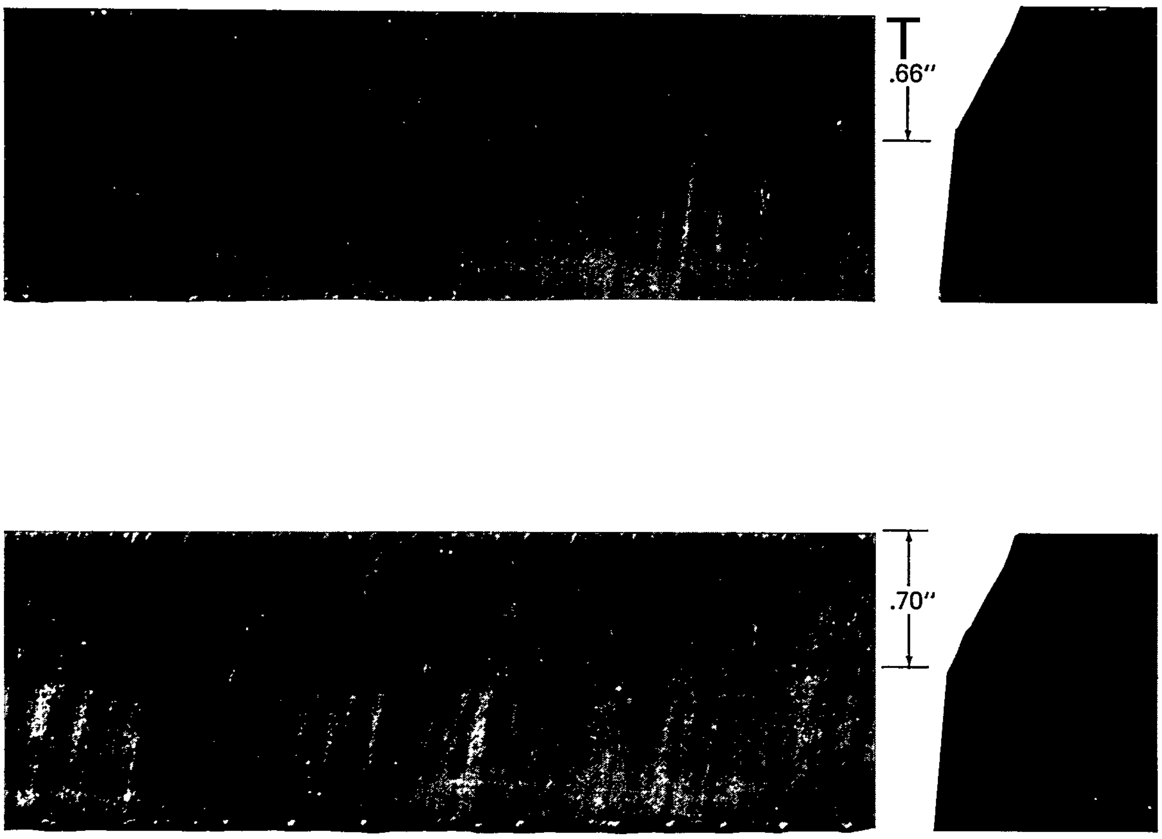
EFFECT OF BEVEL DEPTH ON DROSS FORMATION - 1¼" PLATE



Notes: Bevel Angle=27°.
Nose Angle=6°.
Refer to Table III
for cutting conditions.

Figure 16

EFFECT OF BEVEL DEPTH ON DROSS FORMATION - 1½" PLATE



Notes: Bevel Angle=27°
Nose Angle=6°
Refer to Table III
for cutting conditions.

Figure 17

PREDICTED MAXIMUM BEVEL DEPTH

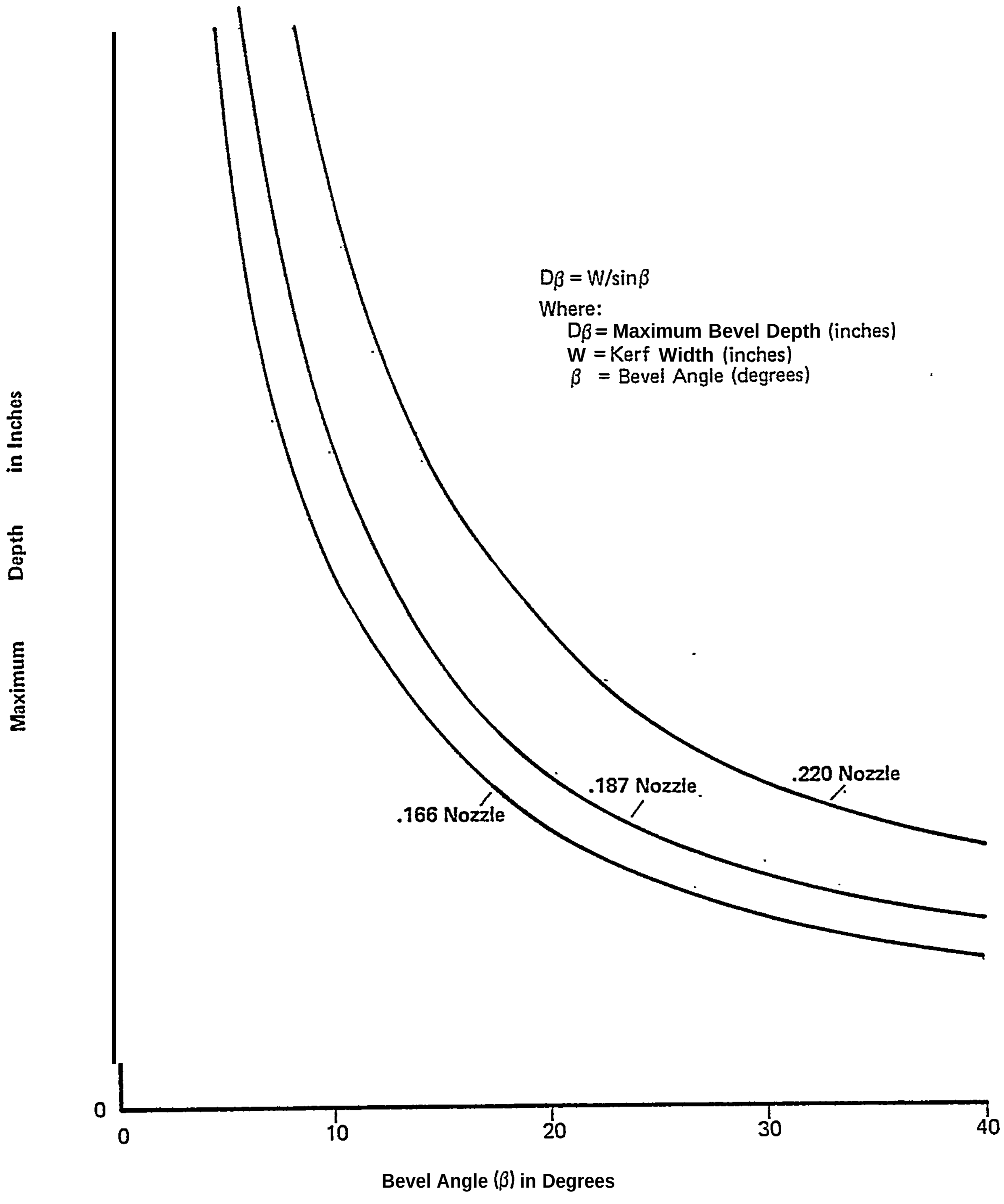


Figure 18

TRIPLE TORCH EDGE PREPARATION

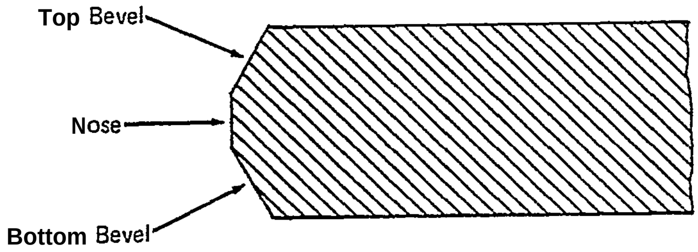


Figure 19

THREE TORCH CUT SEQUENCES

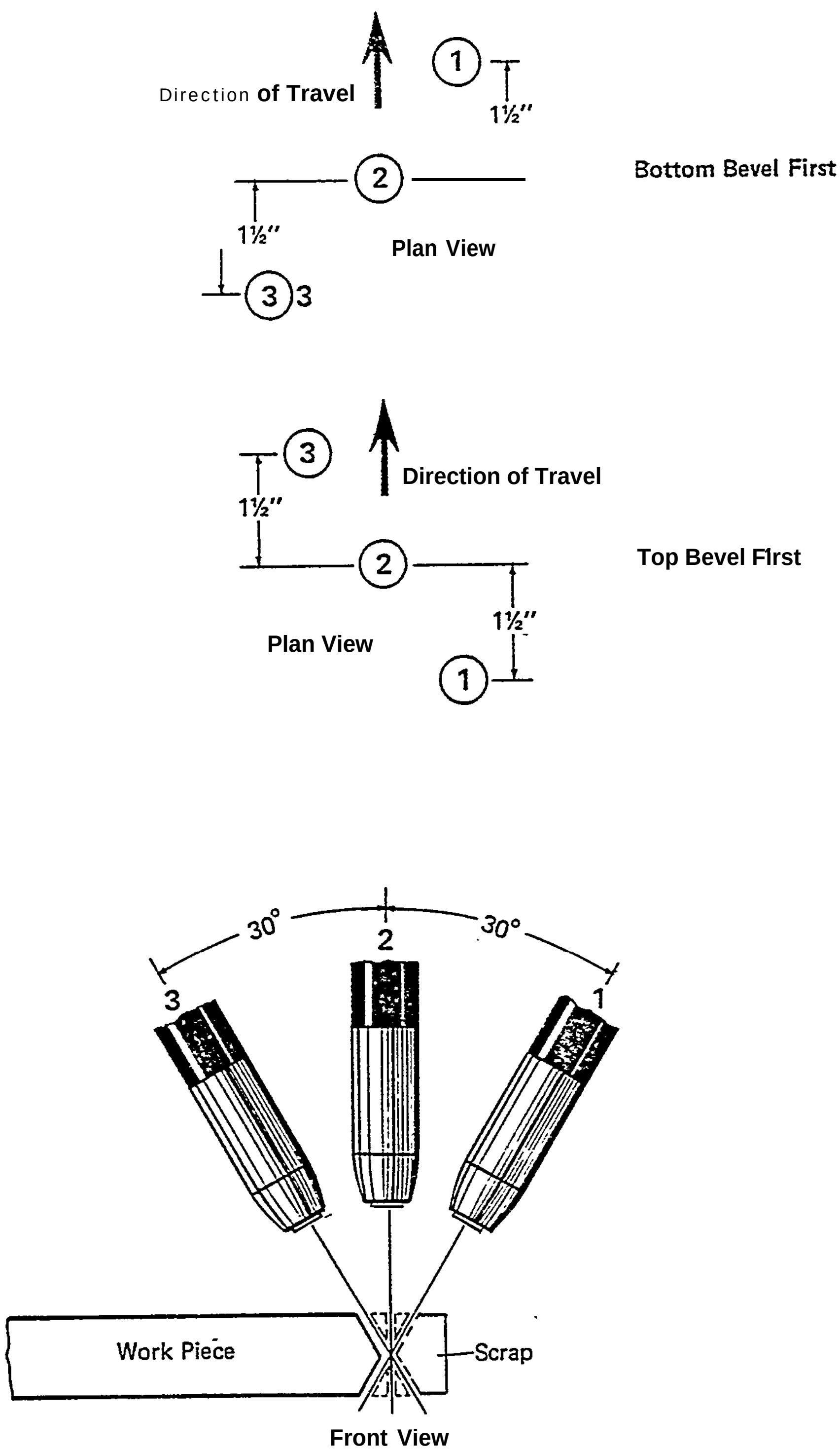


Figure 20

TWO CONDITIONS THAT CAN OCCUR
WHEN USING THE CONVENTIONAL
OXY-FUEL THREE TORCH CUT SEQUENCE

Notes: Dross on top cut cannot be removed.
Both samples were cut under the same conditions.
Cut Sequence-Bottom Bevel first.
Square cut second.
Top Bevel third.

Figure 21

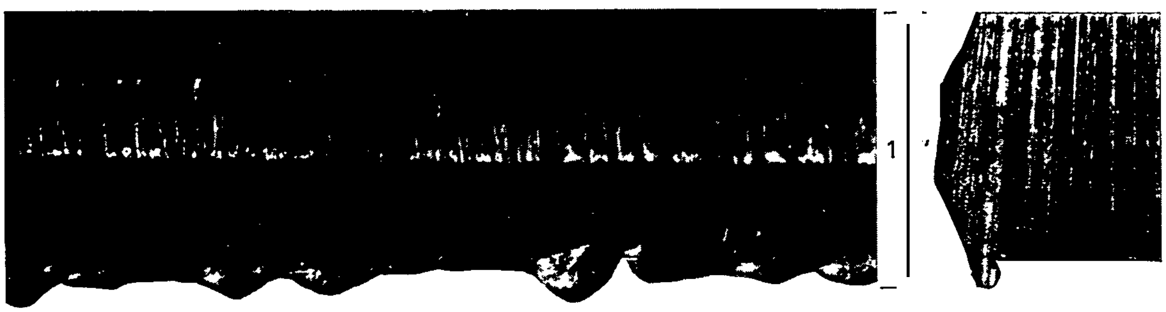
THREE TORCH BEVELS WITH **'TOP** BEVEL **FIRST'** CUT SEQUENCE

Cutting Conditions:

Thickness (inches)	1	1¼
Nozzle Size	.166	.187
Arc Current (amps)	400	500
Arc Voltage (volts)	170	180
Cutting Speed (ipm)	33	35

Figure 22

TWO PASS THREE TORCH BEVELING



Cutting Conditions:

	First Pass Top Bevel and Nose	Second Pass Bottom Bevel
Nozzle Size	.220	.220
Arc Current (amps)	700	700
Arc Voltage (volts)	180	·175
Cutting Speed (ipm)	40	54

Figure 23

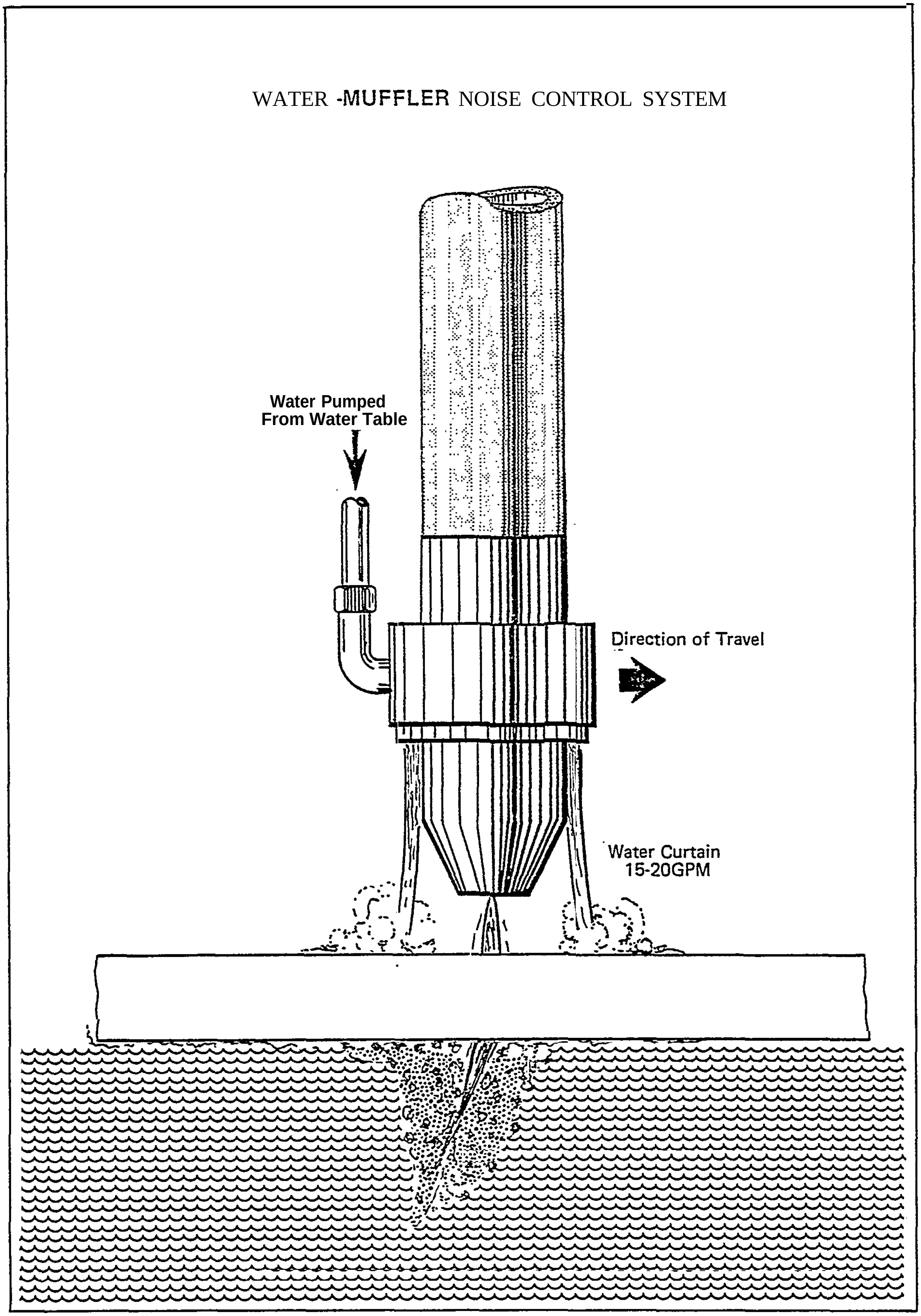

WATER -MUFFLER NOISE CONTROL SYSTEM
Water Pumped
From Water Table
Direction of Travel
Water Curtain
15-20GPM

Figure 24

NOISE PRODUCED BY ONE TORCH
AT VARIOUS BEVEL ANGLES

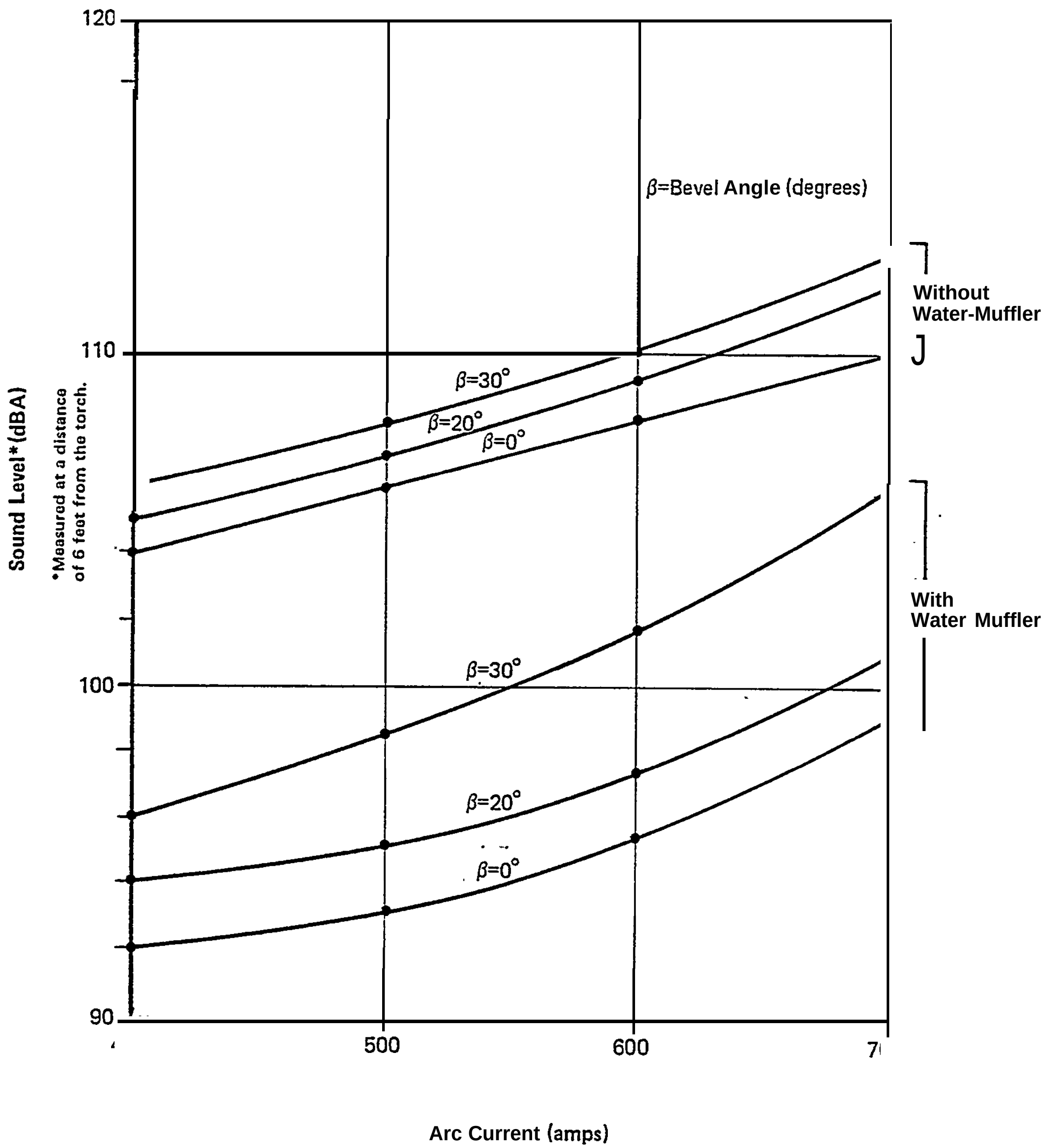
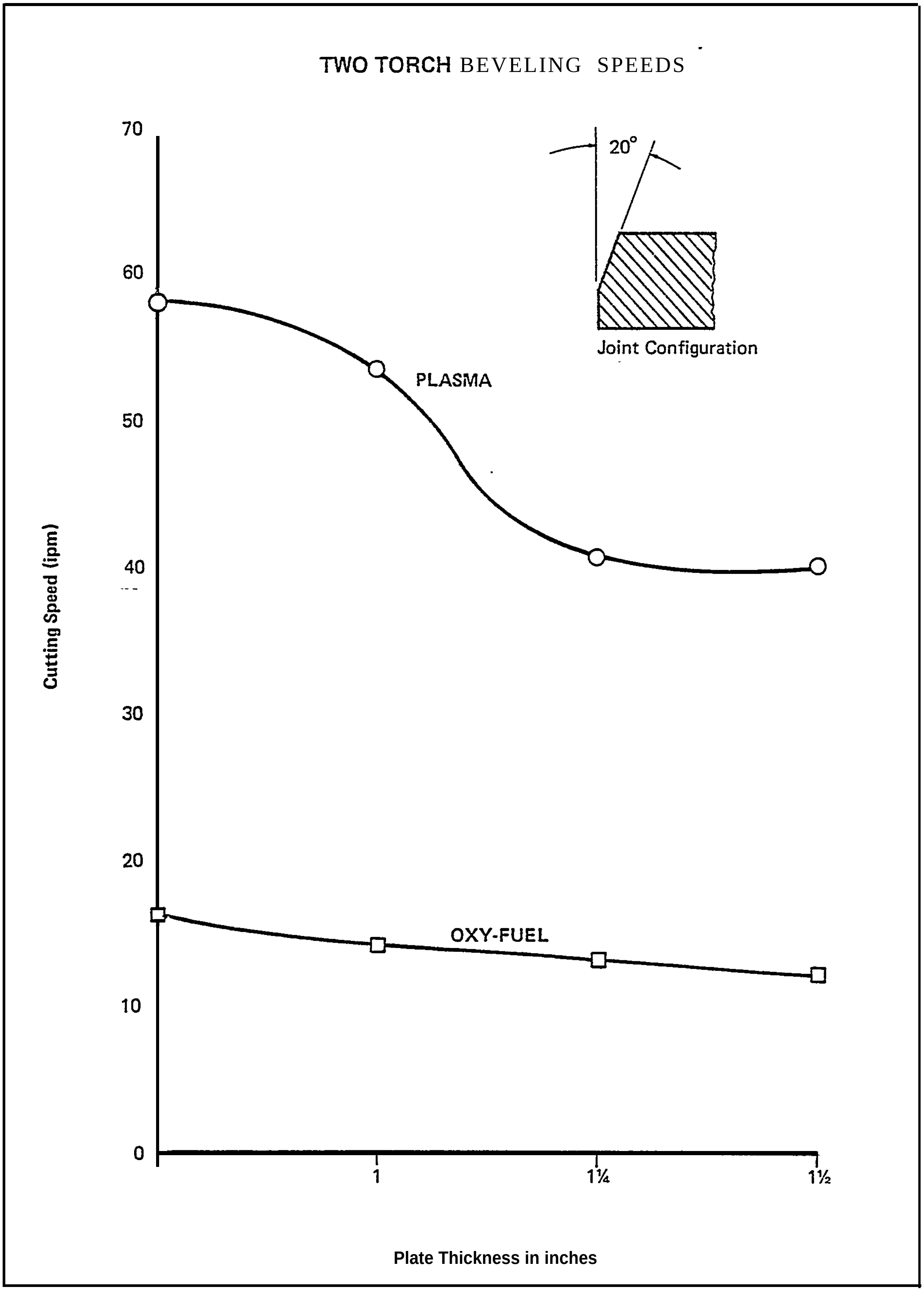


Figure 25



TWO TORCH BEVELING SPEEDS
20°
Joint Configuration
PLASMA
OXY-FUEL
Cutting Speed (ipm)
70
60
50
40
30
20
10
0
1
1¼
1½
Plate Thickness in inches

Figure 26

APPENDICES

APPENDIX I

WATER-INJECTION PLASMA CUTTING

Introduction

Plasma arc cutting was developed 20 years ago primarily for cutting stainless steel and aluminum. Although favorable economically, mild steel was seldom cut with this process because of three fundamental limitations: relatively poor cut quality, equipment reliability, and inability of the earlier cutting machines to handle plasma cutting speeds. As a result of these limitations, plasma cutting did not encounter rapid growth until after Water-injection Plasma Cutting was introduced in 1970.

This relatively new process differs from conventional, "dry" plasma cutting in that water is injected around the arc. The net result is greatly improved cut quality on virtually all metals, including mild steel. Today, because of advances in equipment design and improvements in cut quality, previously unheard of applications, such as multiple torch cutting of mild steel, are becoming commonplace.

Arc Constriction

In the early 1950's, it was discovered that the properties of the open arc, ie, Tig welding arc, could be greatly altered by directing the arc through a water cooled copper nozzle located between an electrode (cathode) and the work (anode). Instead of diverging into an open arc, the nozzle constricts the arc into a small cross section. This action greatly increases the resistive heating of the arc so that both the arc temperature and the voltage are raised. After passing through the nozzle, the arc exits in the form of a high velocity, well collimated and intensely hot plasma jet as shown in Figure AI-1.

In this example, both discharges are operating in argon at 200 amps. The plasma jet is only moderately constricted by the 3/16-inch diameter nozzle, but operates at twice the voltage and produces a much hotter plasma than the corresponding open arc.

The plasma cutting arc is considerably hotter than the example described in Figure AI-1. Greater temperatures are possible because the high gas flow forms a relatively cool boundary layer of gas inside the nozzle bore, thereby allowing a higher degree of arc constriction. The thickness of this boundary layer can be further increased by swirling the cutting gas. This swirling action causes the cool, unionized gas to move radially outward and form a thicker boundary layer. Most mechanized plasma cutting torches swirl the cutting gas to attain maximum arc constriction.

Conventional Plasma Arc Cutting

The plasma jet that is generated by conventional "dry" arc constriction techniques can be used to sever any metal at relatively high cutting speeds. The thickness of plate can range from l/8-inch to a maximum thickness depending on both the current capacity of the torch and the physical properties of the metal. A heavy duty mechanized torch with a current capacity of 1000 amps can cut through 5-inch thick stainless steel and 6-inch thick aluminum. However, in most industrial applications the plate thickness seldom exceeds 1 1/2-inch. In this thickness range, conventional plasma cuts are usually beveled and have a rounded top edge.

Beveled cuts are a result *of* an imbalance in heat input into the cut face. As shown in Figure AI-2, a positive cut angle will result if the heat input into the top of the cut exceeds the heat input into the bottom. One obvious approach to reduce this heat imbalance is to apply the arc constriction principle described in Figure AI-1: Increased arc constriction will cause the temperature profile of the plasma jet to become more uniform and, consequently, the cut will become more square. Unfortunately, the conventional nozzle is limited by the tendency to establish two arcs in series--electrode to nozzle, and nozzle to work. This phenomenon is known as "double arcing" and can damage both the electrode and nozzle.

Water-injection Plasma Cutting

The key to achieving improved cut quality is through increasing arc constriction. In the Water-injection Plasma Cutting process, water is radially injected into the arc *in* a uniform manner as shown in Figure AI-3. The radial impingement of the water around the arc provides a higher degree of arc constriction than can be achieved by conventional means. Arc temperatures in this region are estimated to approach 50,000°K. The net result is improved cut squareness and increased cutting speeds.

Another approach to constricting the arc with water is to develop a swirling vortex of water around the arc. This technique does not perform as well as radial injection because the degree of arc is limited by the high swirl velocities needed to produce a stable water vortex: The centrifugal force created by the high swirl velocity tends to flatten the annular film of water against the inner bore of the nozzle.

Unlike the conventional processes described earlier, optimum cut quality is obtained on all metals with just one cutting gas--nitrogen. This single gas requirement makes the process more economical and easier to use. Nitrogen is ideal because of its superior ability to transfer heat *from* the arc to the workpiece. As illustrated in the equation below, the heat energy E_h, absorbed by nitrogen when it dissociates, is relinquished when it recombines at the workpiece.

$$N_2 + E_h \rightleftharpoons N + N$$

Despite the extremely high temperatures generated at the point where the water impinges the arc, less than 10% of the water is vaporized. The remaining 90% of the water exits from the nozzle in the form of a conical spray which cools the top surface of the workpiece. This additional cooling prevents the formation of oxides on the cut surface. Little water is evaporated at the arc because an insulating boundary layer of steam forms between the plasma and the injected water. This steam boundary layer, referred to as a "Lindenfrost Layer", is the same principle that allows a drop of water to dance around on a hot skillet rather than immediately vaporizing.

Nozzle life is greatly increased with the Water-injection technique because the steam boundary layer insulates the nozzle from the intense heat of the arc, and the water cools the nozzle at the point of maximum arc constriction. The protection afforded by the water-steam boundary layer also allows a unique design innovation: The entire lower portion of the nozzle can be ceramic. Consequently, double-arcing from the nozzle touching the workpiece--the major cause of nozzle destruction--is virtually eliminated.

An important property of these cuts is that when viewed in the direction of the cut, as shown in Figure AI-3, the right side of the kerf is square and the left side of the kerf is slightly beveled. This feature is not caused by Water-injection; rather, it results from the cutting gas which is swirled in a clockwise direction, causing more of the arc energy to be expended on the right side of the kerf. This same asymmetry exists in conventional "dry" cutting when the cutting gas is swirled; however, the difference in cut angle is not so evident because of excessive bevel and rounding of the top edge. In shape cutting applications, this means that the direction of travel must be selected to produce a square cut on the production part.

On the annular shaped part shown in Figure AI-4, the outside cut is made in a clockwise direction so the saved piece is always on the right side of the kerf. Similarly, the inside cut must be made in a counterclockwise direction to maintain a square edge on the inside of the part. In most applications, like the one shown in Figure AI-4, the beveled side of the cut is discarded when evaluating squareness. Counterclockwise swirl rings are available for applications, such as mirror image cutting, where the high quality side must be on the left.

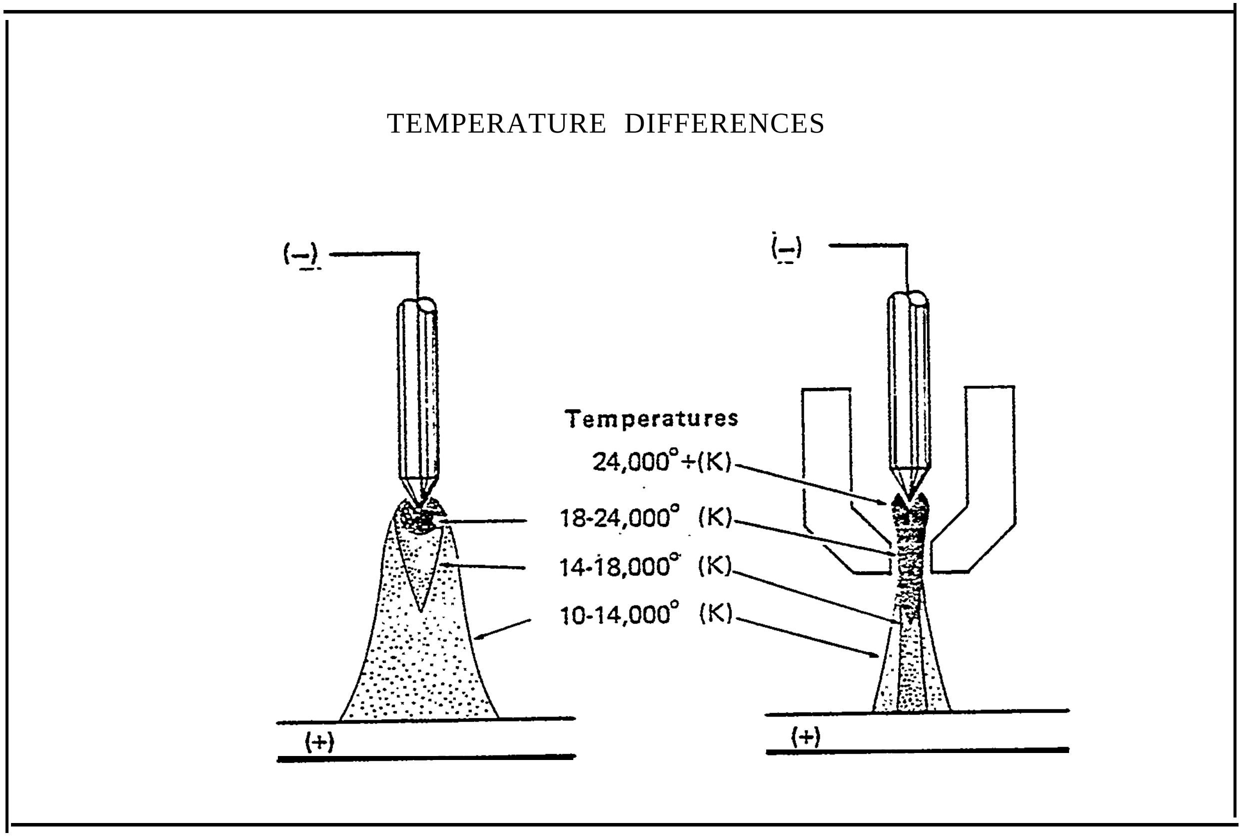


Figure AI-1

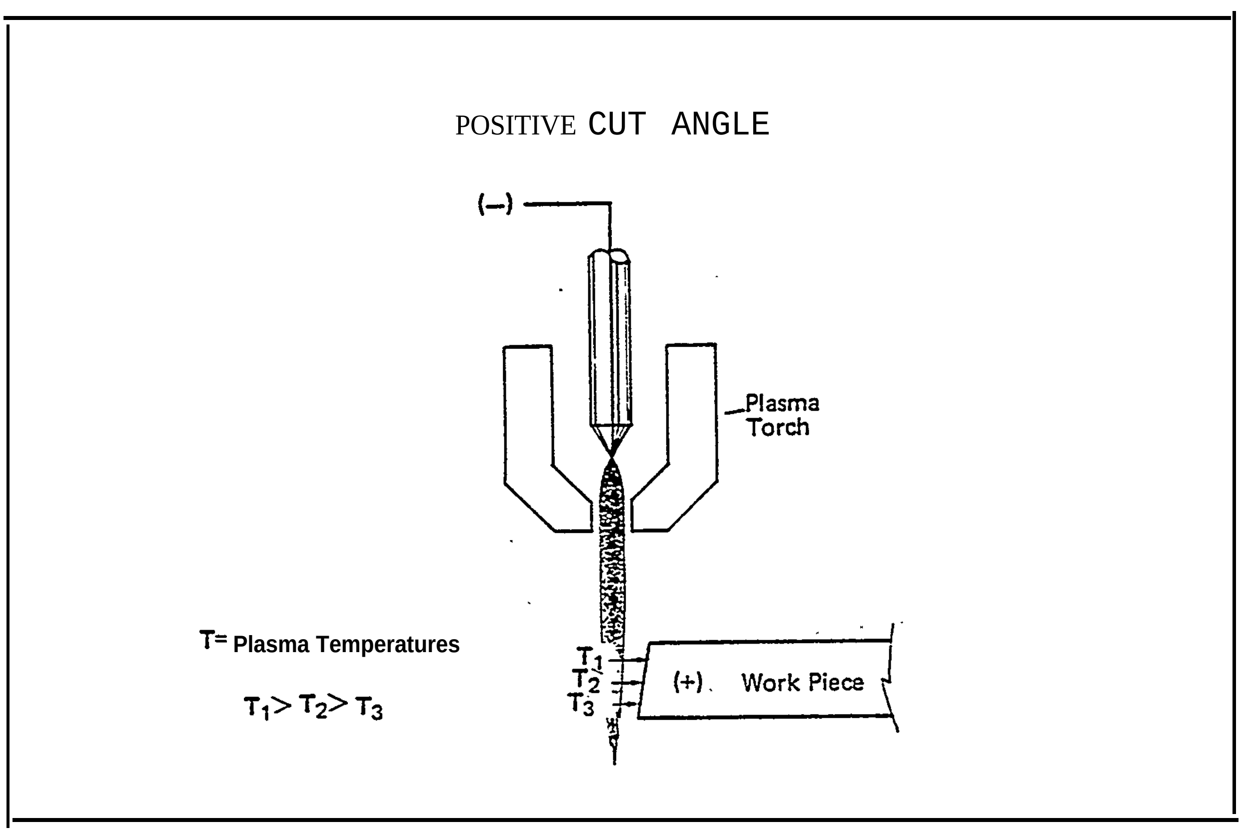


Figure AI-2

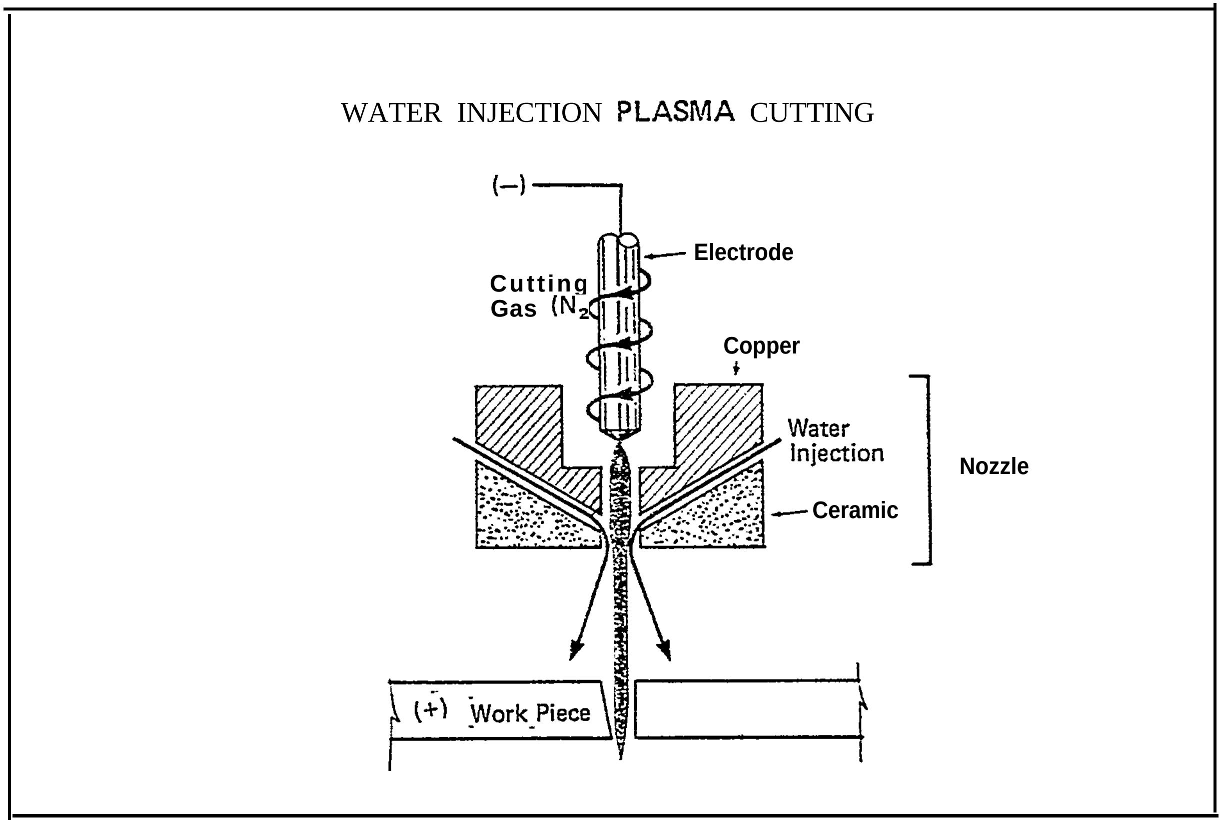


Figure AI-3

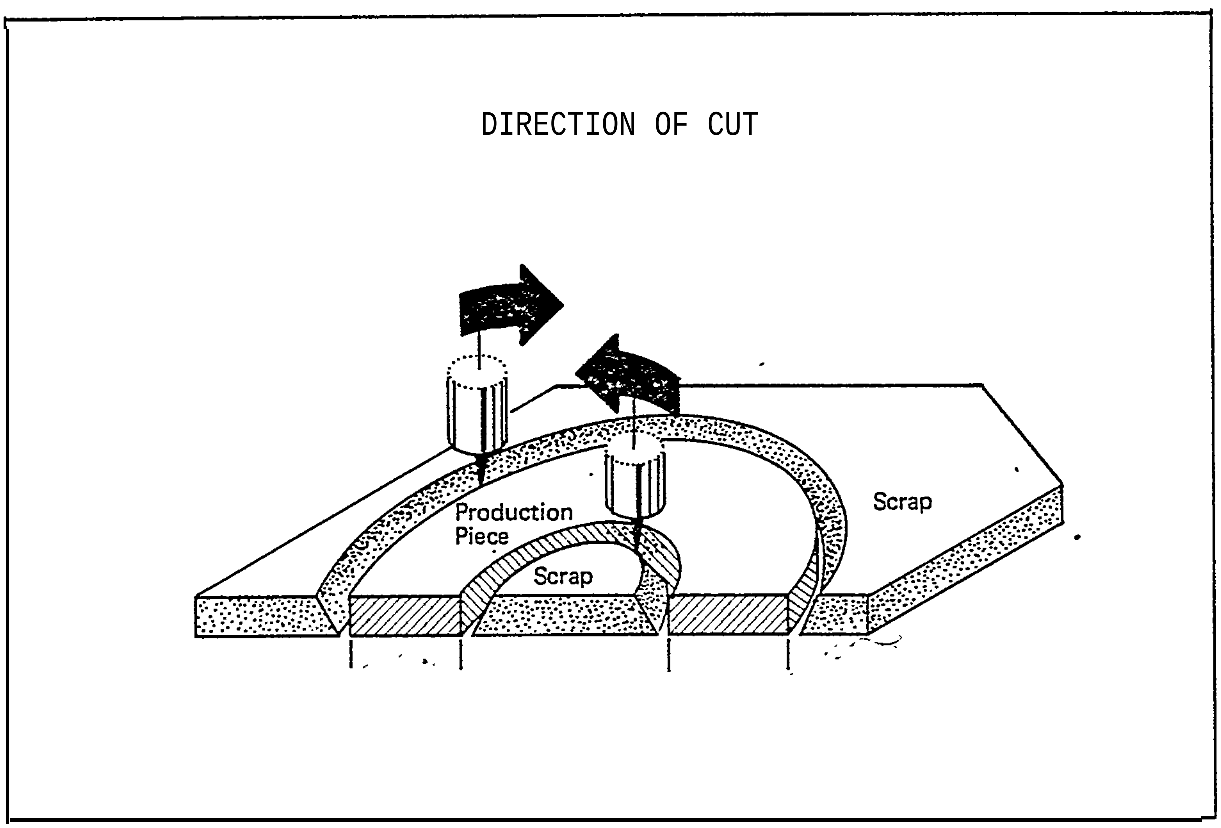


Figure AI-4

APPENDIX II

Parameters Affecting Dross Formation

Dross is resolidified, oxidized metal that adheres to the bottom edge of a cut. The tendency to form dross depends on metallurgical composition, surface condition, cutting speed, and arc current. The influence of these variables, as well as a technique to minimize dross formation, will be described in this section.

The two major cutting parameters that influence dross formation are cutting speed and arc current. If the cutting speed is too low, the kerf will widen and the molten cut face will be outside the high momentum portion of the plasma jet. As a result, the molten metal will not have sufficient momentum to overcome the opposing surface tension force along the bottom cut edge. This type of dross is often called "Low Speed Dross". It can be identified by its heavily oxidized, bubbly appearance. Also, since it appears at low speeds, the lag lines scribed in the cut surface will only have a very slight lag.

As the cutting speed is increased - arc current held constant - the arc will tend to increase in lag-angle and start to fluxuate or "pump" up and down before loosing the cut. This arc instability will create a tenacious dross along the bottom edge of the cut face. Loss of cut will result if the cutting speed is increased much beyond this point.

The minimum speed at which high speed dross is formed can be increased by increasing the arc current. Low speed dross to dross free transition point is essentially independent of arc current. A graph showing the transition line or characteristic where high and low speed dross is formed on 1/2-inch 304 stainless steel, is shown in Figure AII-1. Note that below 225 amps the low speed dross will blend into high speed dross without exhibiting a dross free interval.

The dross-free range define-d in Figure AII-1 determines the practical working range of a nozzle. For a given current setting, the best cut quality is obtained at a speed that falls between the two curves. Excessively high cutting speed will create a positive bevel cut. Therefore, optimum cut quality - square, dross free cuts - is obtained in an operating band between 45% and 55% of "interval speed" (Figure AII-2).

Mild steel can be difficult to cut dross-free. The width of the dross-free interval will depend on surface condition and alloy composition. In general, mill scale plate is the hardest to cut, whereas mild steel sandblasted and painted with a zinc base or iron oxide primer has a relatively wide dross-free interval. The dross-free interval for 1/2-inch mild steel with various surface conditions is compared with 1/2-inch stainless steel in Figure AII-3. Although the actual data can vary somewhat, Figure AII-3 does provide a reasonably accurate comparison.

The tendency to form dross generally increases with increasing plate thickness. One simple means of expanding the dross-free interval is by going to the next largest nozzle size and by increasing the arc current accordingly. This fact is illustrated in Figure AII-4 for 3/4-inch mild steel plate which can be cut with either the .166 or .187 nozzle.

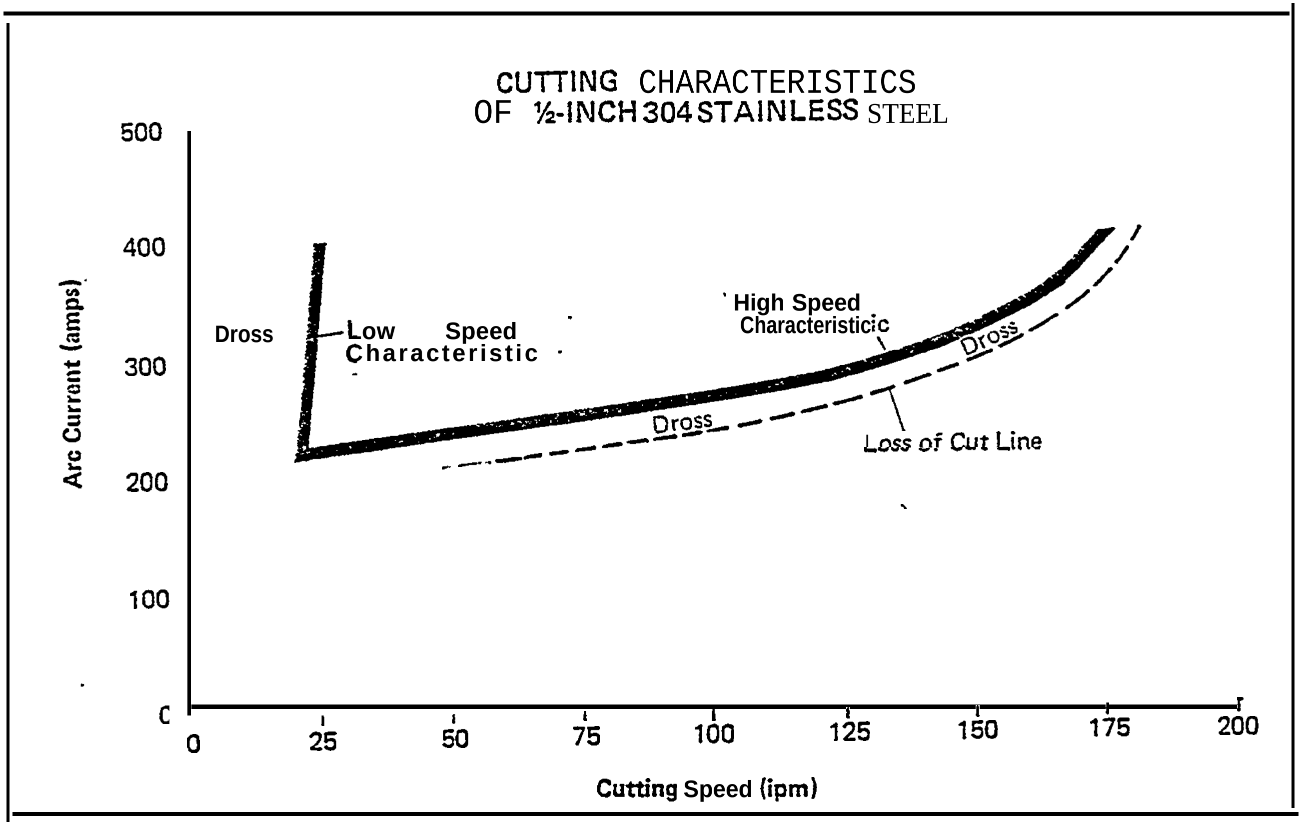


Figure AI I-1

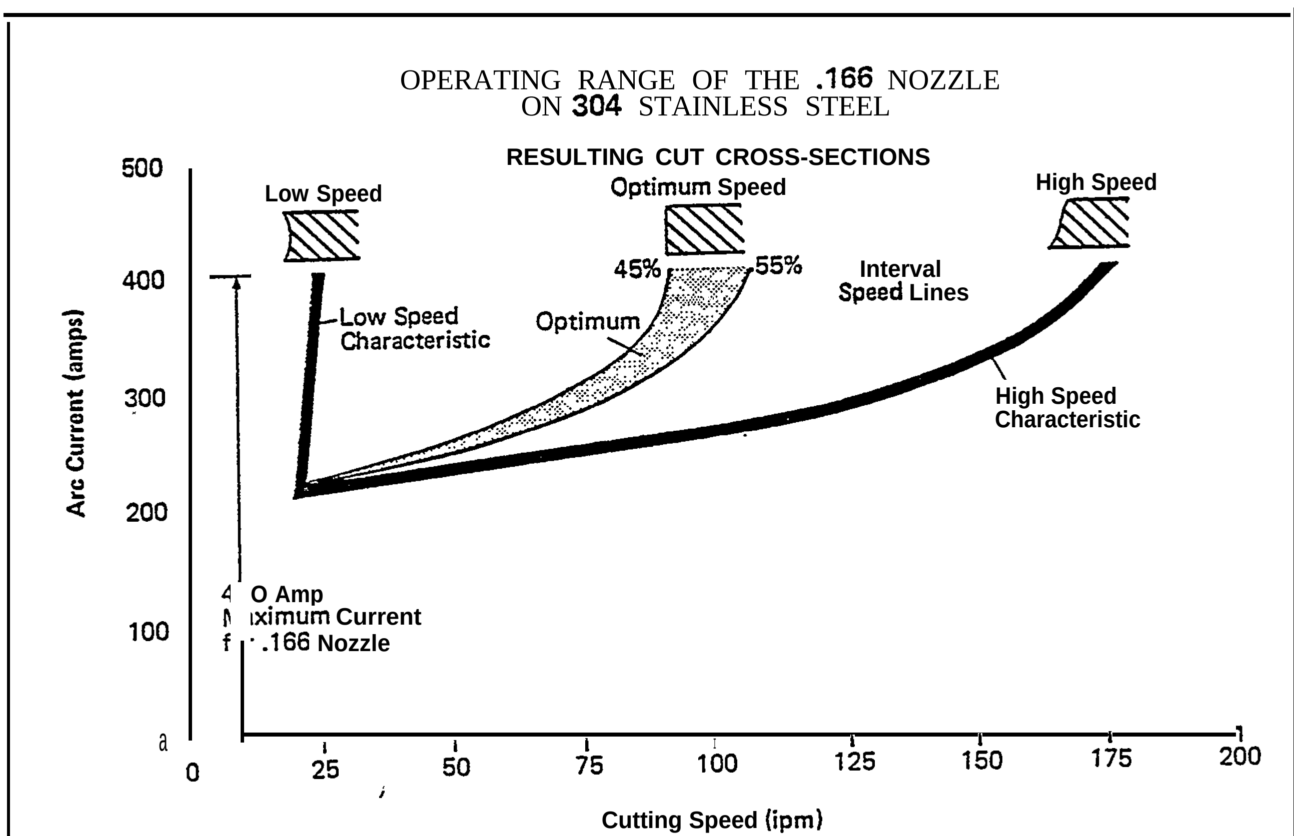


Figure AI I-2

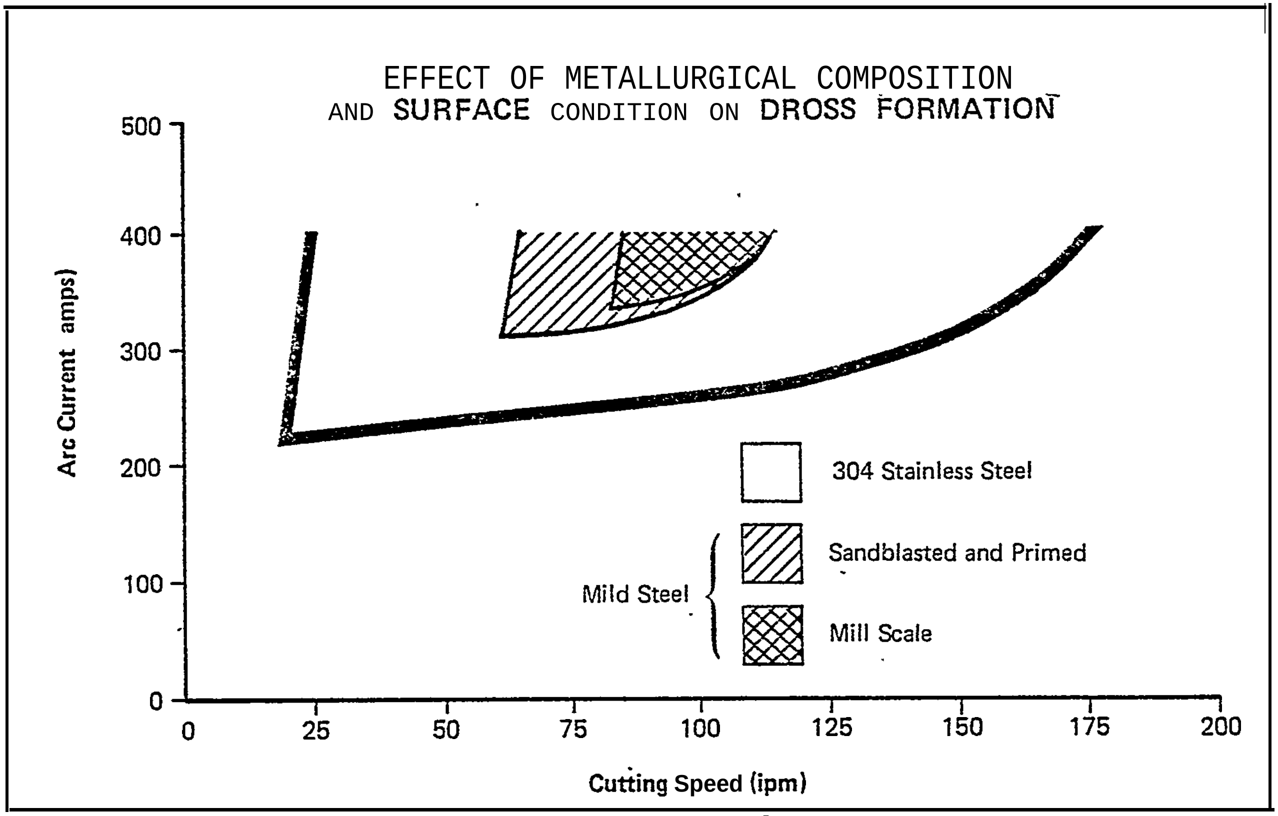


Figure AI I-3

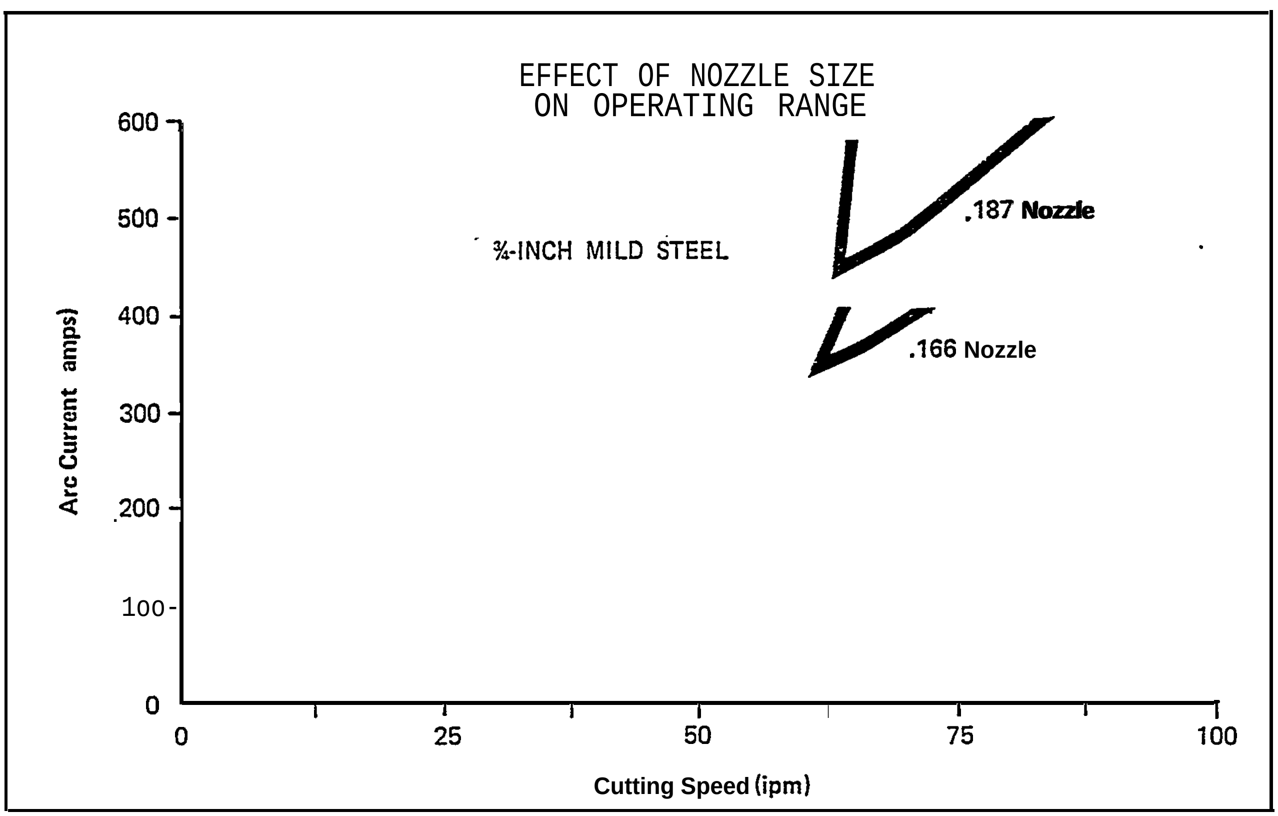


Figure AI I-4

APPENDIX III

Derivation of Predicted Maximum Bevel Depth

Dross-free, two torch edge preparation is only possible when the scrap triangle formed between the two kerfs is non-existent. For a given kerf width and bevel angle, this means that the cut centerline of torch number 1, shown in Figure 3A-1, must be moved toward torch number 2 until the kerf wipes out the scrap triangle. The resulting bevel depth, D_β, that occurs just at the point the scrap triangle disappears is defined as the "Maximum Bevel Depth", D_β (MAX). The purpose of this derivation is to calculate D_β (MAX) as a function of kerf width, W, and bevel angle, β. All of these parameters are defined in Figure 3A-1.

The scrap triangle disappears when torch number 1 is adjusted so that parameter T=0 (see Figure AIII-1 "Maximum Bevel Condition"). Therefore, the maximum bevel depth, D_β (MAX) occurs when the dimensions of triangle $A'BC'$ are S+W and D_β (MAX) +Y. Since these respective dimensions are opposite and adjacent to bevel angle then:

$$(1) \quad \tan\beta = \frac{S + W}{D_\beta\,(MAX) + Y}$$

or

$$(2) \quad D_\beta\,(MAX) = \frac{S + W}{\tan\beta} - Y$$

D_β (MAX) can be expressed in terms of bevel angle, β and kerf width, W by substituting the following equations:

$$(3) \quad Y = \frac{W}{\tan\beta}$$

and

$$(4) \quad S = \frac{W}{\cos\beta}$$

Equations (3) and (4) can be derived by assuming the kerf width, W, is constant for both torches, and then breaking down each parameter into the appropriate trigometric triangles (Figure AIII-1). Therefore, substituting Equations (3) and (4) into Equation (2) we obtain:

$$(5) \quad D_\beta\,(MAX) = \frac{\frac{W}{\cos\beta} + W}{\tan\beta} - \frac{W}{\tan\beta}$$

$$= \frac{W}{\tan\beta\,\cos\beta}$$

$$(6) \quad D_\beta\,(MAX) = \frac{W}{\sin\beta}$$

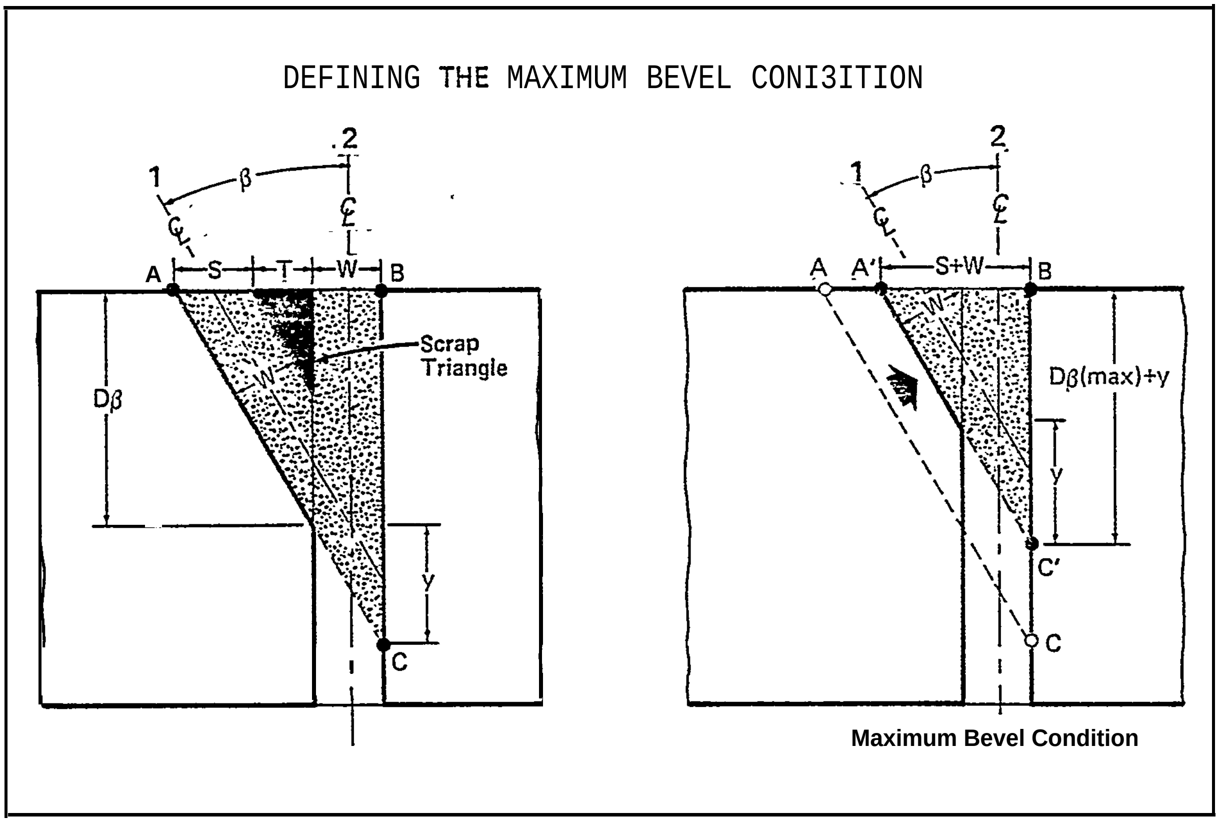


Figure AIII-1